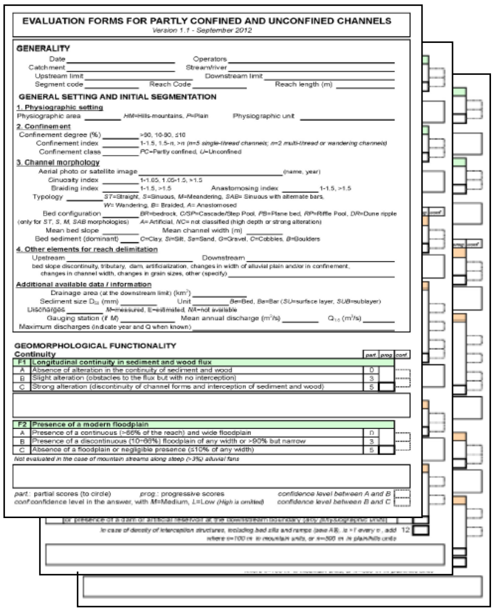
**THEME: Environment (including climate change)**
**TOPIC: ENV.2011.2.1.2-1 Hydromorphology and ecological objectives of WFD**
**Collaborative project (large-scale integrating project)**
**Grant Agreement 282656**
**Duration: November 1, 2011 – October 31, 2015**

# REFORM

## REstoring rivers FOR effective catchment Management




Deliverable D6.2 Part 3

Title Guidebook for the evaluation of stream morphological conditions by the Morphological Quality Index (MQI)

Authors (authors of D6.2 Part 3*) M. Rinaldi[1], N. Surian[2], F. Comiti[3], M. Bussettini[4], B. Belletti[1], L. Nardi[1], B. Lastoria[4], B. Golfieri[2]

[1]UNIFI, [2]University of Padova, [3]Free University of Bozen-Bolzano, [4]ISPRA

Due date to deliverable: 31 July 2015
Actual submission date: 30 October 2015

Project funded by the European Commission within the 7th Framework Programme (2007 – 2013)

Dissemination Level

| | | |
|---|---|---|
| PU | Public | X |
| PP | Restricted to other programme participants (including the Commission Services) | |
| RE | Restricted to a group specified by the consortium (including the Commission Services) | |
| CO | Confidential, only for members of the consortium (including the Commission Services) | |

* Please cite the whole of Deliverable 6.2 as follows:
M. Rinaldi, B. Belletti, M.I. Berga Cano, S. Bizzi, B. Blamauer, K. Brabec, G. Braca, M. Bussettini, F. Comiti, L. Demarchi, D. García de Jalón, M. Giełczewski, B. Golfieri, M. González del Tánago, R. Grabowski, A.M. Gurnell, H. Habersack, S. Hellsten, S. Kaufman, M. Klösch, B. Lastoria, F. Magdaleno Mas, L. Mao, E. Marchese, P. Marcinkowski, V. Martínez-Fernández, E. Mosselman, S. Muhar, L. Nardi, T. Okruszko, A. Paillex, C. Percopo, M. Poppe, J. Rääpysjärvi, M. Schirmer, M. Stelmaszczyk, N. Surian, M. Toro Velasco, W. Van de Bund, P. Vezza, C. Weissteiner (2015) Final report on methods, models, tools to assess the hydromorphology of rivers. Deliverable 6.2, a report in five parts of REFORM (REstoring rivers FOR effective catchment Management), a Collaborative project (large-scale integrating project) funded by the European Commission within the 7th Framework Programme under Grant Agreement 282656.

Please cite Part 3 of Deliverable 6.2 as follows:
M. Rinaldi, N. Surian, F. Comiti, M. Bussettini, B. Belletti, L. Nardi, B. Lastoria, B. Golfieri (2015) Guidebook for the evaluation of stream morphological conditions by the Morphological Quality Index (MQI), Deliverable 6.2, Part 3, of REFORM (REstoring rivers FOR effective catchment Management), a Collaborative project (large-scale integrating project) funded by the European Commission within the 7th Framework Programme under Grant Agreement 282656.

## *Summary*

Background and Introduction to Deliverable 6.2

Work Package 6 of REFORM focuses on monitoring protocols, survey methods, assessment procedures, guidelines and other tools for characterising the consequences of physical degradation and restoration, and for planning and designing successful river restoration and mitigation measures and programmes.

Deliverable 6.2 of Work Package 6 is the final report on methods, models and tools to assess the hydromorphology of rivers. This report summarises the outputs of Tasks 6.1 (Selection of indicators for cost-effective monitoring and development of monitoring protocols to assess river degradation and restoration), 6.2 (Improve existing methods to survey and assess the hydromorphology of river ecosystems), and 6.3 (Identification and selection of existing hydromorphological and ecological models and tools suitable to plan and evaluate river restoration).

The deliverable is structured in five parts. Part 1 provides an overall framework for hydromorphological assessment. Part 2 includes thematic annexes on protocols for monitoring indicators and models. Part 3 (this volume) is a detailed guidebook for the application of the Morphological Quality Index (MQI). Part 4 describes the Geomorphic Units survey and classification System. Part 5 includes a series of applications to some case studies of some of the tools and methods reported in the previous parts.

Summary of Deliverable 6.2 Part 3

This part provides a detailed description of the Morphological Quality Index (MQI), and the related version adapted for monitoring (Morphological Quality Index for monitoring, MQIm). The Morphological Quality Index was originally developed in Italy, and then expanded to other European countries within the context of the REFORM project. The Morphological Quality Index for monitoring (MQIm), has been specifically designed to assess the environmental impact assessment of interventions, including both flood mitigation and restoration actions.

The Evaluation Forms for confined and for partly confined/unconfined streams respectively, a detailed Guide to the Compilation of the Evaluation Forms, which is used to support the application of the two indices, and an Illustrated Guide are provided in the Appendixes of this part.

**Acknowledgements**

REFORM receives funding from the European Union’s Seventh Programme for research, technological development and demonstration under Grant Agreement No. 282656.

# Table of Contents

# 1. The Morphological Quality Index (MQI)

## *1.1 Introduction*

The EU Water Framework Directive (WFD) introduced the term 'hydromorphology', which requires the consideration of any modifications to flow regime, sediment transport, river morphology, and lateral channel mobility. Several methods have been adopted for implementing the WFD in European countries — in most cases coinciding with physical habitat assessment procedures (e.g., RHS, Raven et al., 1997; Lawa, 2000).

A critical analysis of hydromorphological assessment methods has been conducted in the REFORM Deliverable 1.1 (Rinaldi et al., 2013), and summarized in Belletti et al. (2015), with the aim of identifying the main strengths, limitations, gaps, possible integration of different approaches, and needs for further improvements. The main gap identified in most methods is an insufficient consideration of physical processes.

To address this gap, an increasing effort has been recently made to develop methods based on a sounder geomorphological approach, with a stronger consideration of physical processes at appropriate spatial and temporal scales. The River Styles Framework (Brierley and Fryirs, 2005), the *SYRAH* (Système Relationnel d'Audit de l'Hydromorphologie des Cours d'Eau; Chandesris et al., 2008), the *IHG* (Indice Hydrogeomorfologico; Ollero et al., 2007, 2011), the method proposed by Wyżga et al. (2010, 2012), and the Morphological Quality Index (MQI) (Rinaldi et al., 2013) are examples of morphological assessment procedures that are based on a geomorphological approach.

The Morphological Quality Index (MQI) was initially developed to be specifically suitable for the Italian context, i.e. cover the full range of physical conditions, morphological types, degree of artificial alterations, and amount of channel adjustments. During the REFORM project, this method has been verified and expanded to cover the full range of physical conditions (physiographic units, hydrological, and climatic conditions, etc.) and the morphological types of rivers at European scale.

## *1.2 Main characteristics of the method*

The main characteristics and innovative features of the MQI can be summarized as follows (Rinaldi et al., 2013).

(i) The method is based on an *expert judgement* (i.e., a selection of variables, indicators, classes, and relative scores), deriving from the specific knowledge and experience of the authors. This reflects the use of a 'special' rather than a 'natural' classification scheme (Sneath and Snokal, 1973; Kondolf, 1995; Kondolf et al., 2003a).

(ii) The method was designed to comply with *WFD requirements*, but could be used for other purposes in river management.

(iii) Because the method is to be used by environmental or water agencies on a national level, it has been designed to be *relatively simple and not excessively time consuming*. However, its application should be carried out by trained people with an appropriate background and sufficient skills in fluvial geomorphology.

(iv) The method is based on the *consideration of processes* ('process-based') rather than only of channel forms. Aspects such as continuity in sediment and wood flux, bank erosion, lateral mobility, and channel adjustments are taken into account. On the other hand, it is worth reminding the aim of the method, that is to assess morphological quality, and not to get a quantification of processes or an in-depth understanding of channel evolution and future dynamics. A rigorous evaluation of geomorphological processes would imply measurements at different times of process rates (e.g., bank erosion or deposition) or the use of quantitative modelling or analyses (e.g., to assess alterations in sediment transport). Such a quantification is not feasible having in mind the previous point (iii).

(v) The *temporal component* is explicitly accounted for by considering that an historical analysis of channel adjustments provides insight into the causes and time of alterations and into future geomorphic changes. Lack of consideration of the temporal component is considered as one of the main limitations of many of the other geomorphic classification schemes (Kondolf et al., 2003a). In this method, we explicitly include indicators of channel adjustments in the evaluation of river morphological quality.
(vi) Concerning the *spatial scales*, the multiscale, hierarchical approach developed in REFORM by Gurnell et al. (2014) is adopted, where the 'reach' (i.e., a section of river along which present boundary conditions are sufficiently uniform, commonly a few kilometres in length) is the basic spatial unit for the application of the evaluation procedure.
(vii) *Morphological conditions* are evaluated exclusively in terms of physical forms and processes without any reasoning on their consequences or implications in terms of ecological state. This means that a high morphological quality is not necessarily related to a good ecological state, although this is commonly the case. In fact, it is widely recognised that the geomorphic dynamics of a river and the functioning of natural physical processes spontaneously promote the creation and maintenance of habitats and ensure the ecosystems' integrity (e.g., Kondolf et al., 2003b; Brierley and Fryirs, 2005; Wohl et al., 2005; Florsheim et al., 2008; Fryirs et al., 2008; Habersack and Piégay, 2008).
(viii) *Reference conditions*. According to the WFD, the reference state is given by 'undisturbed' conditions showing no or only 'very minor' human impacts (European Commission, 2003). A detailed discussion on reference conditions for hydromorphology is reported in Rinaldi et al. (2013). In synthesis, reference conditions for the MQI entail a river reach in dynamic equilibrium, where the river is performing those morphological functions that are expected for a specific morphological typology, and where artificiality is absent or does not significantly affect the river dynamics at the catchment and reach scale.

(ix) The MQI is not suitable for *assessing small changes* in morphological quality and, more generally, for monitoring the effects of a specific management or restoration action. For this aim, the Morphological Quality Index for monitoring (MQIm: see chapter 2) should be used.

(x) Though the MQI does not provide an explicit "*target vision*" for possible river restoration, the evaluation structure provides a rational framework that is potentially useful for supporting analyses of interventions and impacts and for identifying and prioritizing management strategies, adequate restoration schemes, and measurement programmes.

## *1.3 General setting and segmentation*

The first phase of the method is aimed at providing a general setting of physical conditions and subdividing the river network into relatively homogeneous reaches, defined as sections of river along which present boundary conditions are sufficiently uniform (i.e., with no significant changes in valley setting, channel slope, imposed flow and sediment load; Brierley and Fryirs, 2005; Gurnell et al., 2014).

This delineation phase coincides with the multi-scale hierarchical framework developed in REFORM (see Gurnell et al., 2014 for more details). The final product of this phase is the subdivision of the river network into reaches. These are commonly a few kilometres in length and represent the elementary spatial units for the assessment of the morphological conditions.

**Table 1.1 Summary of the general setting and segmentation procedure (modified from Rinaldi et al., 2013).**

| Steps | Criteria | Outputs |
|---|---|---|
| *Step 1: general setting and identification of landscape (or physiographic) units and segments* | - geological and geomorphological characteristics | - *Landscape units*<br>- *Segments* |
| *Step 2: definition of confinement typologies* | - lateral confinement | - *Confinement typologies:*<br>confined (*C*)<br>partly confined (*PC*)<br>unconfined (*U*) |
| *Step 3: identification of morphological typologies* | - planimetric characteristics (sinuosity, braiding, and anabranching indices) | - *Morphological typologies:*<br>*Confined*: single thread, wandering, braided, anabranching<br>*partly confined - unconfined*: straight, sinuous, meandering, wandering, braided, anabranching |
| *Step 4: other elements for reach delineation* | - further discontinuities in hydrology, bed slope, characteristic geomorphic units, bed sediment calibre, channel width, floodplain width | - *Reaches* |

According to the original version of the MQI (Rinaldi et al., 2012, 2013), four steps can be used during the delineation procedure (Table 1.1), including some slight modification from the original version to ensure full consistency with the REFORM delineation framework. The four steps are summarised in Table 1.1 and in the following sub-sections (more details and illustrations are reported in the Appendix 4: *Illustrated Guide to the Compilation of the Evaluation Forms*).

### 1.3.1 Step 1: Physiographic setting

***Aim***: derive a general setting of the physiographic context and identify macro-areas (landscape or physiographic units) and macro-reaches (segments) with similar morphological characteristics.

***Information/data necessary***: watershed area, dominant lithologies, climate and hydrologic regime, land use, longitudinal profiles.

***Methods***: geological, geomorphological, and land use maps; existing studies; hydrological data collection and analysis; Remote sensing /GIS; field reconnaissance.

***Results***: division of the catchment into landscape units and of the rivers into segments. The latter are macro-reaches defined by the intersection of channel network with landscape units, and by additional factors (e.g., major changes of valley setting, major tributary confluences).

***Description***: based on existing material, the main **landscape units** in the catchment are identified. They can be included in the following main **physiographic settings**: (1) *mountains*; (2) *hills*; (3) *plains*. Intermediate cases (e.g., hilly mountain areas) can be also defined.

The portions of streams included within a landscape unit are defined as **segments**. Within a same landscape unit, the river may be further divided into more segments depending on additional factors, including major changes of valley setting (confined, partly-confined, unconfined, as well as continuity of alluvial deposits) and gradient, major tributary confluences (significantly increasing upstream catchment area, river discharge). Segments normally have a length to the order of some km (mountain areas) and up to tens of km (lowland areas).

### 1.3.2 Step 2: Confinement

***Aim***: define confinement in more detail, and sub-divide segments based on confinement.

***Information/data necessary***: width of the entire floodplain, confinement degree, confinement index.

***Methods***: Remote sensing /GIS; topographic and geological maps.

***Results***: division of segments based on confinement.

***Description***: to analyze the confinement in detail, two parameters are used: (1) confinement degree; (2) confinement index.

(1) **Confinement degree**. This evaluates the lateral confinement in the longitudinal valley direction. It corresponds to the percentage of banks not directly in contact with the plain but with hillslopes or *ancient terraces*, over the total length of the two banks (Brierley and Fryirs, 2005). The *plain* is here identified with the entire *floodplain*, generally constituted by alluvial sediments (also indicated as *alluvial plain*), and is normally identified on geological maps with "present alluvium" or "Holocene alluvium", while *ancient terraces* are older. *Recent terraces* generated by historical bed incision (e.g., during the last 100÷200 years, as very frequently occurred in many European countries) are not considered as *ancient terraces* and for the purpose of the confinement are part of the entire *floodplain*. In addition to a chronological criterion, further factors for defining the confinement can be the difference of elevation and the erodibility of the material. For example, a Holocene terrace of 10÷15 m is not part of the floodplain. Vice versa, a Pleistocene terrace separated by a difference in level of a few meters can be considered as part of the floodplain, except when the material is strongly cemented. Finally, the floodplain is not always constituted by alluvial sediments. In Northern Europe, many plains have been generated by *fluvio-glacial* or *fluvio-lacustrine* processes, and are characterised by a large sediment size variability, ranging from very fine (lacustrine deposits) to coarse (glacial or fluvio-glacial deposits). In these cases, the floodplain is intended in a broader sense as a surface that does not constitute an element of confinement for the 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).

Once the elements of confinement (hillslopes and ancient terraces) have been delimited, three cases can be distinguished based on the *confinement degree* (Brierley and Fryirs, 2005; Rinaldi et al., 2013; Gurnell et al., 2015):

- **Confined channels**: more than 90% of the banks are directly in contact with hillslopes or ancient terraces. The floodplain is limited to some isolated pockets (< 10%).
- **Partly confined channels**: banks are in contact with the floodplain for a length from 10 to 90%.
- **Unconfined channels**: less than 10% of the bank length is in contact with hillslopes or ancient terraces. In fact, the floodplain is nearly continuous, and the river has no lateral constraints to its mobility.

In some cases, the confinement degree previously defined is not sufficient to appropriately define the confinement characteristics. In fact, it is not infrequent (particularly in mountain areas) to have streams with a very narrow (some meters) but quite continuous floodplain on the sides before entering in contact with the hillslopes. According to the previous definitions, such streams may fall into the categories of partly confined or unconfined, while for the aims of this method it would be more appropriate to consider them as confined. Therefore, an additional parameter is used here which takes into account the width of the floodplain, defined as follows.

(2) **Confinement index**. It is defined here as the ratio between the floodplain width (including the channel) and the channel width. Consequently, the index is inversely proportional to the confinement: a minimum value of 1 indicates that the floodplain and channel coincide (i.e. there is no floodplain), while the index increases when the floodplain increases its width relatively to the channel width. Based on the confinement index, the following classes are defined:

- *high confinement*: index ranging from 1 to 1.5;
- *medium confinement*: index ranging from 1.5 to *n*;
- *low confinement*: index higher than *n*;

where *n* = 5 for single-thread channels, and *n* = 2 for multi-thread or transitional (wandering) morphologies. The highest value for single-thread channels reflects the fact that a sufficiently wide floodplain is needed for these channels to develop completely free meanders, equal to about 4.5 times the channel width (Leopold and Wolman, 1957).

Based on the confinement degree and confinement index, the three final classes of confinement can be defined, according to Table 1.2.

Table 1.2 Definition of final confinement classes by combining confinement degree and confinement index (from Rinaldi et al., 2012).

| Confinement class | Description |
|---|---|
| *Confined* | All cases with confinement degree > 90% |
| | Confinement degree from 10% to 90% and confinement index ≤ 1.5 |
| *Partly confined* | Confinement degree from 10% to 90% and confinement index > 1.5 |
| | Confinement degree < 10% and confinement index ≤ *n* |
| *Unconfined* | Confinement degree < 10% and confinement index > *n* |

### 1.3.3 Step 3: Channel morphology

***Aim***: define and classify channel morphology.

***Information/data necessary***: confinement, sinuosity index, braiding index, anastomosing index (bed configuration).

***Methods***: Remote sensing /GIS; field reconnaissance.

***Results***: division of segments based on channel morphology.

***Description***: criteria for the classification of channel morphology are slightly differentiated for partly confined - unconfined channels and for confined channels.

*Partly confined and unconfined channels* are classified based on their planimetric characteristics, therefore using the following indices (see also Gurnell et al., 2015): (1) *sinuosity index*; (2) *braiding index*; (3) *anabranching index*.

- **Sinuosity index** (***Si***) is defined as the ratio between the distance measured along the (main) channel and the distance measured following the direction of the overall planimetric course (or 'meander belt axis' for single thread rivers).
- **Braiding index** (***Bi***) is defined as the number of active channels at baseflow separated by bars.
- **Anabranching index** (***Ai***) is defined as the number of active channels at baseflow separated by vegetated islands.

Based on these parameters, the following six Basic River Typologies (*BRT*: see D6.2 Part 1 or Gurnell et al., 2015) of partly confined and unconfined channels are defined (Table 1.3):

- *Single-thread channels*: straight, sinuous, meandering
- *Transitional channels*: wandering
- *Multi-thread channels*: braided, anabranching.

Further morphologies, described by the Extended River Typology (*ERT*: see D6.2 Part 1 or Gurnell et al., 2015), can be identified during the Step 4 and/or during the characterization and assessment stages.

Table 1.3 Criteria and threshold values of indices or other distinctive characteristics for the morphological classification of partly confined and unconfined channels (modified from Rinaldi et al., 2012, 2013, and from Gurnell et al., 2015). n.a.: not applied.

| Typology | Sinuosity index (*Si*) | Braiding index (*Bi*) | Anabranching index (*Ai*) |
|---|---|---|---|
| Straight (*ST*) | **1 ≤ *Si* < 1.05** | 1÷1.5 (normally approx. 1) | 1÷1.5 (normally approx. 1) |
| Sinuous (*S*) | **1.05 ≤ *Si* < 1.5** | 1÷1.5 (normally approx. 1) | 1÷1.5 (normally approx. 1) |
| Meandering (*M*) | ≥ 1.5 | 1÷1.5 (normally approx. 1) | 1÷1.5 (normally approx. 1) |
| Wandering (*W*) | n.a. | 1 < *Bi* < 1.5 | 1 < *Ai* < 1.5 |
| Braided (*B*) | n.a. | ≥1.5 | <1.5 |
| Anabranching (*A*) | n.a. | 1÷1.5 | ≥ 1.5 |

*Confined channels* are first divided into two broad categories (single-thread, multi-thread or wandering). For single-thread, sinuosity is not meaningful as it is determined by the valley rather than the channel planform. These channels are not further classified at this stage, because it is not possible to make accurate distinctions based on other characteristics (e.g., bed configuration) from remotely sensed sources. Transitional and multi-thread confined reaches are identified using the same criteria as for unconfined and partly-confined channels (see below). In conclusion, only four *BRT* of confined channels are discriminated: single-thread (straight-sinuous), wandering, braided, anabranching.

During a following phase of field characterization, *bed configuration* can be classified as well as the Extended River Typology can be applied. The following bed morphologies are distinguished (Montgomery and Buffington, 1997; Gurnell et al., 2015):

- *Bedrock channels;*
- *Colluvial channels;*
- *Alluvial channels*: cascade, step pool, plane bed, riffle pool, dune ripple;
- *Artificial bed.*

### 1.3.4 Step 4: Other elements for reach delineation

***Aim***: finalize the delineation of reaches accounting for additional factors.

***Information/data necessary***: hydrologic discontinuities (tributaries, dams), artificiality, width of floodplain, channel width, longitudinal profile.

***Methods***: Remote sensing/GIS; longitudinal profile by topographic maps; field reconnaissance.

***Results***: segments are divided into reaches, representing the basic spatial unit for the application of the MQI.

***Description***: the following additional aspects are considered in this step as criteria for a further division into reaches.

- ***Change in geomorphic units***. Within a reach with a same channel morphology (according to step 3), a distinct change in the typical assemblage of geomorphic units can be noted and used as an additional criterion for sub-dividing the reach. Changes in geomorphic units and/or in sediment size (see later) are reflected in a change of river type, according to the Extended River Typology (*ERT*: see D6.2 Part 1 or Gurnell et al., 2015). For example, a sinuous reach may be characterised by a first portion with continuous, alternate bars (type 12 of the *ERT*) and a second part with only occasional bars (type 13 of the *ERT*): in this case, two distinct sinuous reaches can be distinguished characterised by a different pattern of bars.
- ***Discontinuities in bed slope***. This is particularly important in the case of confined channels where important and abrupt changes in bed slope can be noted from the longitudinal profile.
- ***Tributaries***. Tributaries determining significant changes in flow discharge or sediment transport can be considered in this step.
- ***Dams and other artificial elements***. Artificial discontinuities are mainly identified with *dams*, which are always assumed as a limit between reaches. Similarly, *check dams* or diversion structures of relevant sizes are normally considered as a limit of the reach. Furthermore, heavily artificial streams (*type 0* of the *BRT*, see D6.2 Part 1 or Gurnell et al., 2015) are also considered in this step, such as a stream reach crossing an urban area, or a mountain stream with bed revetments and/or a sequence of consolidation check dams.
- ***Change in confinement and/or size of the floodplain***: in some cases, this can be considered as an additional criterion.
- ***Changes in sediment size***: cases of a considerable and sudden change in sediment size, e.g. a passage from gravel-bed to sand-bed, can be considered a criterion of separation in different reaches. This can be reflected in a change of river type, according to the Extended River Typology. For example, a sinuous reach may be characterised by a first portion with a gravel bed (type 13 of the *ERT*), and a second part with a sand-bed (type 17 of the *ERT*): in this case, two distinct sinuous reaches can be distinguished characterised by a different sediment size.

## *1.4 Structure and key components of the evaluation procedure*

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

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

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

Finally, indicators of *channel adjustments* are included in the evaluation. Adjustments caused by human disturbances can shift within a fluvial system in space and time, so that an alteration in channel form and process may be related to disturbances that occurred in the past and/or in a different location of the watershed (Simon and Rinaldi, 2006). Channel adjustments focus on relatively recent morphological changes (i.e., about the last 100 years) that are indicative of a systemic instability related to human factors. In fact, human-induced disturbances greatly compress timescales for channel adjustments (e.g., Rinaldi and Simon, 1998; Simon and Rinaldi, 2006). However, channel changes that are not clearly related to human disturbances that occurred during this temporal frame (e.g., changes related to large floods) could be recognised and not considered as alteration. To this end, the information relative to the indicators of artificiality is useful (e.g., intense sediment removal activity or the presence of dams in the watershed that could be interpreted as causes of intense channel adjustments). As anticipated above, the historical river conditions (past 100 years) are not considered as a reference state (see previous section) but as a comparative situation to infer whether channel adjustments occurred over the last decades.

Indicators of geomorphic *functionality* and *channel adjustments* can be considered as 'response indicators', whereas indicators of *artificiality* as 'pressure indicators'. Including both 'response' and 'pressure' indicators provides a basis for understanding causes of current river conditions.

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

The *reference conditions* are defined considering the previous three components (functionality, artificiality, channel adjustments). As for the first component, the reference conditions are given by the channel form and processes that are expected for the morphological typology under examination. For artificiality, the reference is given by the absence or only slight presence of human intervention in terms of flow and sediment regulation, hydraulic structures, and river maintenance activities. If elements of artificiality exist, they should produce only small negligible effects on the channel morphology and river processes. Finally, concerning channel adjustments, the channel could also be aggrading or incising in the long term (e.g. the last 100-200 years), but not going through major changes of channel morphology caused by human factors.

The overall evaluation is carried out by making a synergic use of two types of methods: *GIS analysis* (using available databases and remotely sensed data such as aerial photos and LiDAR DTMs) and *field surveys*.

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

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

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

## *1.5 Indicators*

The complete set of indicators (28) can be schematically represented by crossing the aspects (in rows) and components (in columns) described in the previous section (Table 1.4).

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

A summary of indicators, with assessed parameters, assessment methods, and ranges of application for each of them, is reported in Table 1.5, while a detailed description of each indicator is reported in the *Guide to the Compilation of the MQI Evaluation Forms* (Appendix 3).

**Table 1.4 List of indicators as a function of the main aspects (continuity, morphology, vegetation) and components of assessment (functionality, artificiality, channel adjustments).**

| | | Functionality | Artificiality | Channel adjustments |
|---|---|---|---|---|
| **Continuity** | - longitudinal | F1 | A1, A2, A3, A4, A5 | |
| | - lateral | F2, F3, F4, F5 | A6, A7 | |
| **Morphology** | - channel pattern | F6, F7, F8 | A8 (A6) | CA1 |
| | - cross section | F9 | (A4, A9, A10) | CA2, CA3 |
| | - bed substrate | F10, F11 | A9, A10, A11 | |
| **Vegetation** | | F12, F13 | A12 | |

**Table 1.5 Definition, assessed parameters, assessment methods, and ranges of application of each indicator (modified from Rinaldi et al., 2013).**

| Indicators and assessed parameters | Assessment methods | Ranges of application |
|---|---|---|
| **F1 – Longitudinal continuity in sediment and wood flux**<br>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**<br>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**<br>Presence and length of elements of disconnection (e.g., roads) within a buffer 50-m wide for each river side | *Remote sensing–GIS*: identification and measurement of length of disconnecting elements (quantitative); *field survey*: checking disconnecting elements (qualitative) | *C* |
| **F4 – Processes of bank retreat**<br>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**<br>Width and longitudinal length of an erodible corridor, i.e., area without relevant structures (e.g., bank protections, levées) or infrastructures (e.g., houses, roads) | *Remote sensing–GIS*: measurement of width and longitudinal length (quantitative) | *PC–U* |
| **F6 – Bed configuration – valley slope**<br>Identification of bed configuration (i.e., cascade, step pool, etc.) in case of presence of transversal structures and comparison with expected bed configuration based on valley slope | *Topographic maps*: mean valley slope (quantitative); *field survey*: identification of bed configuration (qualitative) | single-thread *C;* not evaluated for bedrock streams, and for deep streams when observation of the bed is not possible |
| **F7 – Planform pattern**<br>Percentage of the reach length with alteration of 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**<br>Presence/absence of landforms in the floodplain (e.g., oxbow lakes, secondary channels, etc.) | *Remote sensing* and/or *field survey*: identification and checking of fluvial forms (qualitative) | *PC–U;* evaluated only in the case of meandering rivers within a lowland plain physiographic unit |
| **F9 – Variability of the cross section**<br>Percentage of the reach length with alteration of the natural heterogeneity of cross section expected for that river type caused by human factors | *Field survey*: identification/checking (qualitative); *remote sensing–GIS:* identification and measurement of length of altered portions (quantitative) | All typologies; not evaluated in the case of straight, sinuous or meandering channels with natural absence of bars (lowland rivers, low gradients and/or low bedload) |

**Table 1.5 (continued)**

| Indicators and assessed parameters | Assessment methods | Ranges of application |
|---|---|---|
| **F10 – Structure of the channel bed**<br>Presence/absence of alterations of bed sediment (armouring, clogging, bedrock outcrops, bed revetments) | *Field survey*: visual assessment (qualitative) | All typologies; not evaluated for bedrock or sand-bed rivers, and for deep channels when observation of the bed is not possible |
| **F11 – Presence of in-channel large wood**<br>Presence/absence of large wood | *Field survey*: visual assessment (qualitative) | All typologies; not evaluated above the tree-line and in streams with natural absence of riparian vegetation |
| **F12 – Width of functional vegetation**<br>Mean width (or areal extension) of functional vegetation in the fluvial corridor potentially connected to channel processes | *Remote sensing–GIS:* identification and measurement of mean width of functional vegetation (quantitative) | All typologies; not evaluated above the tree - line and in streams with natural absence of riparian vegetation |
| **F13 – Linear extension of functional vegetation and presence of emergent aquatic macrophytes**<br>Longitudinal length of functional vegetation along the banks with direct connection to the channel; presence/absence of emergent aquatic macrophytes | *Remote sensing–GIS:* identification and measurement of longitudinal length of functional vegetation (quantitative)<br>*Field survey*: visual assessment of emergent aquatic macrophytes (qualitative) | All typologies; not evaluated above the tree - line and in streams with natural absence of riparian vegetation<br>Aquatic vegetation evaluated only in low-energy streams |
| **A1 – Upstream alteration of flows**<br>Amount of changes in discharge caused by interventions upstream (dams, diversions, spillways, retention basins, etc.) | *Hydrological data*: evaluation of reduced/increased discharge caused by interventions (quantitative). In absence of available data, the assessment is based on presence of intervention and its use (qualitative) | All typologies |
| **A2 – Upstream alteration of sediment discharges**<br>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**<br>Amount of alterations of discharge caused by interventions within the reach | See A1 | All typologies |
| **A4 – Alteration of sediment discharge in the reach**<br>Typology and spatial density of structures intercepting bedload (check dams, weirs) along the reach | *Remote sensing–GIS* and/or *database of interventions:* identification and number of structures (quantitative) | All typologies |
| **A5 – Crossing structures**<br>Spatial density of crossing structures (bridges, fords, culverts) | *Remote sensing–GIS* and/or *database of interventions:* identification and number of structures (quantitative) | All typologies |
| **A6 – Bank protections**<br>Length of protected banks (walls, rip-raps, gabions, groynes, bioengineering measures) | *Remote sensing–GIS* and/or *database of interventions:* length of structures (quantitative) | All typologies |

**Table 1.5 (continued)**

| Indicators and assessed parameters | Assessment methods | Ranges of application |
|---|---|---|
| **A7 – Artificial levées**<br>Length and distance from the channel of artificial levées | *Remote sensing–GIS* and/or *database of interventions:* length and distance of structures (quantitative) | *PC–U* |
| **A8 – Artificial changes of river course**<br>Percentage of the reach length with documented artificial modifications of the river course (meander cutoff, relocation of river channel, etc.) | *Historical /bibliographic information* and/or *database of interventions* (quantitative) | *PC–U* |
| **A9 – Other bed stabilization structures**<br>Presence, spatial density and typology of other bed-stabilizing structures (sills, ramps) and revetments | *Remote sensing–GIS* and/or *database of interventions:* identification, number or length of structures (quantitative) | All typologies |
| **A10 – Sediment removal**<br>Existence and relative intensity of past sediment mining activity (over the last 100 years, with 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**<br>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**<br>Existence and relative intensity (selective or total) of riparian vegetation cuts during the last 20 years | *Database of interventions* and/or *information available by public agencies; field survey:* additional evidence (qualitative) | All typologies; not evaluated above the tree - line and in streams with natural absence of riparian vegetation |
| **CA1 – Adjustments in channel pattern**<br>Changes in channel pattern from 1930s to 1960s based on changes in sinuosity, braiding, and anastomosing indices | *Remote sensing–GIS* (quantitative) | All typologies; evaluated only for sufficiently large channels |
| **CA2 – Adjustments in channel width**<br>Changes in channel width from 1930s to 1960s | *Remote sensing–GIS* (quantitative) | All typologies; evaluated only for sufficiently large channels |
| **CA3 – Bed-level adjustments**<br>Bed-level changes over the last 100 years | *Cross sections / longitudinal profiles* (if available); *field survey*: evidence of incision or aggradation (qualitative/quantitative) | All typologies; evaluated in case field evidence or information is available |

## *1.6 Classes and scores of the indicators*

The classes and corresponding scores of the indicators are briefly illustrated as follows and listed in Tables 1.6, 1.7, and 1.8. As anticipated earlier, the scoring system was developed using the expert judgement of the authors, implying that the scores assigned to each indicator and the limits among classes are arbitrary. Scores and classes were defined and subsequently improved based on the results of a testing phase (Rinaldi et al., 2013). Scores have remained unchanged in this extended version, in order to ensure data comparability when applied to different European countries.

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

For each indicator, we started by defining reference conditions for that indicator, corresponding to the absence or negligible presence of alterations (class A), and a value of 0 was assigned to this class. For the indicators of functionality, a score of 2 to 3 was assigned to the intermediate class of alteration (class B), and a score of 5 to 6 to class C (highest alteration), depending on the relative importance attributed to each indicator. For some indicators (e.g., *F2* and *F10*), a fourth class was added to better highlight the different levels of alteration.

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

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

An additional rule was defined for the cases of extremely dense and dominant presence of artificial elements along the reach, such as transversal structures, bank protections, levées, and bed revetments (indicators *A4*, *A6*, *A7*, and *A9*, respectively). This rule was included to adequately rank river reaches with only one or just a few types of artificial elements but at very large extensions and/or density, heavily affecting the overall morphological conditions (e.g., completely embanked reaches in urbanized areas; steep mountain creeks with staircase-like sequences of grade-control structures). Without this "extra-penalty", the assignation of class C to only a few artificiality indicators would result in an underestimation of artificiality (and thus to the overestimation of morphological quality). To weight these cases more effectively, rather than defining an additional class, an extra score of 6 or 12 was assigned and added only to the numerator of Eq. (1).

**Table 1.6 Indicators of geomorphological functionality: description of classes and definition of scores.**

| Indicator | Classes | Score |
|---|---|---|
| **F1** | A - absence of alteration in the continuity of sediment and wood | 0 |
| | B - slight alteration (obstacles to the flux but with no interception) | 3 |
| | C - significant alteration (complete interception of sediment and wood) | 5 |
| **F2** | A - presence of a continuous (>66% of the reach) and wide modern floodplain (>*nW*, where *n* = 1 or 2 for wandering – braided or for single thread - anabranching channels, respectively, and *W* = channel width) | 0 |
| | B1 - presence of a discontinuous (10 ÷ 66%) but wide modern floodplain or > 66% but narrow | 3 |
| | B2 - presence of a discontinuous (10 ÷ 66%) and narrow modern floodplain | 2 |
| | C - absence of a modern floodplain or negligible presence (≤10% of any width) | 5 |
| **F3** | A - full connectivity between hillslopes and river corridor (>90%) | 0 |
| | B - connectivity for a significant portion of the reach (33 ÷ 90%) | 3 |
| | C - connectivity for a small portion of the reach (≤33%) | 5 |
| **F4** | A - bank erosion occurs for >10% and is distributed along >33% of the reach | 0 |
| | B – bank erosion occurs for ≤10%, or for >10% but concentrated along ≤33% of the reach, or significant presence (>25%) of eroding banks by mass failures | 2 |
| | C - complete absence (≤2%) of retreating banks, or widespread presence (>50%) of unstable banks by mass failures | 3 |
| **F5** | A - presence of a potentially erodible corridor (*EC*) for a length > 66% of the reach and wide (>*nW*, where *n* = 1 or 2 for wandering – braided or for single thread - anabranching channels, respectively, and *W* = channel width) | 0 |
| | B - presence of a narrow (≤*nW*) potentially *EC* for >66%, or wide but for 33 ÷ 66% of the reach | 2 |
| | C - presence of a potentially *EC* of any width but for ≤33% of the reach | 3 |
| **F6** | A- bed forms consistent with the mean valley slope | 0 |
| | B - bed forms not consistent with the mean valley slope | 3 |
| | C - complete alteration of bed forms for the presence of an artificial bed | 5 |
| **F7** | A - absence (<5%) of alteration of the natural heterogeneity of geomorphic units and channel width | 0 |
| | B - alteration for a limited portion of the reach (≤33%) | 3 |
| | C - consistent alteration for a significant portion of the reach (>33%) | 5 |
| **F8** | A - presence of floodplain landforms (oxbow lakes, secondary channels, etc.) | 0 |
| | B - presence of traces of floodplain landforms (abandoned during the last decades) but with possible reactivation | 2 |
| | C - complete absence of floodplain landforms | 3 |
| **F9** | A - absence (≤5%) of alteration of the cross-section natural heterogeneity | 0 |
| | B - presence of alteration for a limited portion of the reach (≤33%) | 3 |
| | C - presence of alteration for a significant portion of the reach (>33%) | 5 |
| **F10** | A - natural heterogeneity of bed sediments and no significant clogging | 0 |
| | B - evident armouring (*PC–U* only) or clogging in various portions of the site | 2 |
| | C1 - evident and widespread (>90%) armouring (*PC–U* only) or clogging, or occasional substrate outcrops (*PC–U* only) | 5 |
| | C2 - widespread substrate outcrops (>33% of the reach) (*PC–U* only) or widespread substrate alteration by bed revetments (>33% of the reach) | 6 |
| **F11** | A – significant presence of large wood along the whole reach | 0 |
| | B - negligible presence of large wood for ≤50% of the reach | 2 |
| | C - negligible presence of large wood for >50% of the reach | 3 |
| **F12** | A - wide connected functional vegetation (*PC-U:* >*nW*, where *n* = 1 or 2 for wandering – braided or for single thread - anabranching channels, respectively, and *W* = channel width; *C:* >90% of hillslopes, 50 m from each bank) | 0 |
| | B - intermediate width of connected functional vegetation (*PC-U:* 0.5 *W* ÷ *nW*; *C*: 33 ÷ 90% of hillslopes, 50 m from each bank) | 2 |
| | C - narrow connected functional vegetation (*PC-U*: ≤0.5 *W*; *C*: ≤33% of hillslopes, 50 m from each bank) | 3 |
| | C - riparian vegetation ≤33%, or <90% but negligible presence of aquatic vegetation | 5 |

**Table 1.6 (continued).**

| Indicator | Classes | Score |
|---|---|---|
| **F13** | A - linear extension of riparian vegetation >90% of maximum available length and significant presence of aquatic vegetation | 0 |
| | B - riparian vegetation 33 ÷ 90%, or riparian >90% but negligible aquatic vegetation, or riparian ≤33% but significant presence of aquatic vegetation | 3 |
| | C - riparian vegetation ≤33%, or <90% but negligible presence of aquatic vegetation | 5 |

**Table 1.7 Indicators of artificiality: description of classes and definition of scores.**

| Indicator | Classes | Score |
|---|---|---|
| **A1** | A - no significant alteration (≤10%) of channel-forming discharges and *Q* with return interval >10 years | 0 |
| | B - significant alteration (>10%) of *Q* with return interval > 10 years | 3 |
| | C - significant alteration (>10%) of channel-forming discharges | 6 |
| **A2** | A - absence or negligible presence of structures of interception of sediment fluxes | 0 |
| | B1 - presence of dams with drainage area 5 ÷ 33%, and/or weirs or check dams with total interception of bedload and drainage areas 33 ÷ 66%, and/or weirs or check dams with partial or no interception of bedload and drainage areas >33% (*plain/hills areas*) or >66% (*mountain areas*) | 3 |
| | B2 - presence of dams for drainage area 33 ÷ 66%, and/or weirs or check dams with total interception of bedload and drainage areas >66% | 6 |
| | C1 - presence of dams for drainage area >66% | 9 |
| | C2 - presence of a dam at the upstream boundary of the reach | 12 |
| **A3** | A - no significant alteration (≤10%) of channel-forming discharges and *Q* with return interval > 10 years | 0 |
| | B - significant alteration (>10%) of *Q* with return interval > 10 years | 3 |
| | C - significant alteration (>10%) of channel-forming discharges | 6 |
| **A4** | A - absence of structures of sediment flux interception (dams, check dams, weirs) | 0 |
| | B – *channels with S≤1%:* consolidation check dams and/or abstraction weirs (including instream retention basins) ≤1 every 1000 m; *steep channels (S>1%):* consolidation check dams/weirs ≤1 every 200 m and/or one or more open check dams (including instream retention basins) | 4 |
| | C - *channels with S≤1%:* consolidation check dams and/or abstraction weirs (including instream retention basins) >1 every 1000 m; *steep channels (S>1%):* consolidation check dams >1 every 200 m and/or one or more retention check dams<br>Or presence of a dam or artificial reservoir at the downstream boundary (*any bed slope*) | 6 |
| | *In case of density of interception structures, including bed sills and ramps (A9), is >1 every d1, add* | 6 |
| | *In case of density of interception structures, including bed sills and ramps (A9), is >1 every d2, add* | 12 |
| | *d1=150 m and d2=100 m in steep channels, d1=750 m and d2=500 m in channels with S≤1%* | |
| **A5** | A - absence of crossing structures (bridges, fords culverts) | 0 |
| | B - presence of some crossing structure (≤1 every 1000 m on average in the reach) | 2 |
| | C - presence of numerous crossing structures (>1 every 1000 m on average in the reach) | 3 |
| **A6** | A - absence or localized presence of bank protections (≤5% total length of the banks) | 0 |
| | B - presence of protections for ≤ 33% total length of the banks (sum of both banks) | 3 |
| | C - presence of protections for > 33% total length of the banks (sum of both banks) | 6 |
| | *In case of high density of bank protections (>50%) add* | 6 |
| | *In case of extremely high density of bank protections (>80%) add* | 12 |

**Table 1.7 (continued).**

| Indicator | Classes | Score |
|---|---|---|
| **A7** | A - levées absent or distant, or presence of levées close or in contact ≤ 10% total length of the banks | 0 |
| | B - medium presence of levées close and/or in contact (in contact ≤ 50% bank length) | 3 |
| | C - high presence of levées close and/or in contact (in contact > 50% bank length) | 6 |
| | *In the case of high density of bank-edge levées (>66%) add* | 6 |
| | *In the case of extremely high density of bank-edge levées (>80%) add* | 12 |
| **A8** | A - absence of artificial changes of river course in the past (meanders cut-off, channel diversions, etc.); | 0 |
| | B - presence of changes for ≤ 10% of the reach length | 2 |
| | C - presence of changes for > 10% of the reach length | 3 |
| **A9** | A - absence of structures (bed sills/ramps) and absent or localised (≤ 5%) revetments | 0 |
| | B - limited presence of structures (≤ 1 every *n*, where *n* = 200 m for *mountain areas*, *n* = 1000 m for *plain/hills areas*) and or revetments (≤ 15% impermeable and/or ≤ 25% permeable) | 3 |
| | C1 - presence of many structures (> 1 every *n*) and/or significant bed revetments (≤ 33% impermeable and/or ≤ 50% permeable) | 6 |
| | C2 - presence of impermeable bed revetments > 33% and/or permeable revetments > 50% | 8 |
| | *In the case of high density of bed revetment (impermeable>50% or permeable>80%) add* | 6 |
| | *In the case of extremely high density of bed revetment (impermeable>80%) add* | 12 |
| **A10** | *PC–U*: | |
| | A - absence of recent (last 20 years) and past (over the last 100 years) significant sediment removal activities | 0 |
| | B1 – sediment removal activity in the past but absent during last 20 years | 3 |
| | B2 – recent sediment removal activity (last 20 years) but absent in the past | 4 |
| | C – sediment removal activity either in the past and during last 20 years | 6 |
| | *C*: | |
| | A - absence of significant sediment removal activities during the last 20 years | 0 |
| | B - localized sediment removal activities during the last 20 years | 3 |
| | C - widespread sediment removal activities during the last 20 years | 6 |
| **A11** | A - absence of removal of woody material at least during the last 20 years | 0 |
| | B – partial removal of woody material during the last 20 years | 2 |
| | C - total removal of woody material during the last 20 years | 5 |
| **A12** | A - no cutting interventions on riparian vegetation (last 20 years) and aquatic vegetation (last 5 years) | 0 |
| | B - selective cuts and/or clear cuts over ≤ 50% of the reach (last 20 years) and partial or no cutting of aquatic vegetation (last 5 years), or no cutting of riparian but partial or total cutting of aquatic vegetation | 2 |
| | C - clear cuts over > 50% of the reach (last 20 years), or selective cuts and/or clear cuts of riparian vegetation ≤50% of the reach but total cutting of aquatic vegetation (last 5 years) | 5 |

**Table 1.8 Indicators of channel adjustments: description of classes and definition of scores.**

| Indicator | Classes | Score |
|---|---|---|
| **CA1** | A - absence of changes in channel pattern from 1930s – 1960s | 0 |
| | B - change to a similar channel pattern from 1930s – 1960s (*PC–U*) or change of channel pattern from 1930s – 1960s (*C*) | 3 |
| | C - change to a different channel pattern from 1930s – 1960s (only *PC–U*) | 6 |
| **CA2** | A - absent or limited changes (≤15%) from 1930s – 1960s | 0 |
| | B - moderate changes (15 ÷ 35%) from 1930s – 1960s (*PC–U*) or changes >15% from 1930s – 1960s (*C*) | 3 |
| | C - intense changes (>35%) from 1930s – 1960s (only *PC–U*) | 6 |
| **CA3** | A - negligible bed-level changes (≤ 0.5 m) | 0 |
| | B - limited or moderate bed-level changes (0.5 ÷ 3 m) | 4 |
| | C1 - intense bed-level changes (> 3 m) | 8 |
| | C2 – very intense bed-level changes (> 6 m) (only *PC–U*) | 12 |

## *1.7 Calculation of the Morphological Quality Index (MQI)*

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

$$MAI = Stot/Smax \quad (1)$$

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

The Morphological Quality Index is then defined as

$$MQI = 1 - MAI = 1 – Stot/Smax \quad (2)$$

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

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

As previously mentioned, the overall assessment procedure is carried out by using two different **evaluation forms**: one for confined channels, and one for partly confined and unconfined channels (see Appendices 1 and 2, respectively). An *electronic format* of the evaluation forms is available at http://wiki.reformrivers.eu, allowing to automatically calculate the indicators ones the input values are typed.

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

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

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

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

Additionally, the MQI can be divided in its various components, and a series of *sub-indices* can be calculated (see Sub-indices in Appendix 3).

## *1.8 Application of the MQI*

This section details some practical information concerning the application of the MQI.

### 1.8.1 Expertise

The application of the MQI should be carried out by people with appropriate background knowledge of the underlying principles in fluvial geomorphology as well as being sufficiently trained. Similarly to other fields of river sciences (e.g., freshwater biology), application without the necessary background and skills could seriously affect the success of the assessment.

### 1.8.2 Working phases and time required

The sequence of working phases is summarised as follows, with specific reference to the assessment phase, i.e. the application of the MQI to a given delimited reach.

*1. Collection of existing material*

It is assumed that the general setting and segmentation phase has already been carried out. Should segmentation not be available, a minimum delineation can be achieved only for the specific portion or reach under investigation. This will require the collection of additional material (see section 1.3).

Once the reach delineation has been established, this phase will focus on collecting data and information mainly at the reach scale. These include: (i) the most recent remote sensed images (aerial photos or satellite images with sufficiently high resolution) representing the current river conditions; (ii) historical aerial photos (between about the 1930s and 1960s); (iii) map layer of interventions (when available), including existing information on sediment and vegetation management by public agencies. Information on relevant structures responsible for the alteration of flows and/or bedload interception is necessary for the sub-catchment upstream from the reach.

*2. Preliminary remote sensing - GIS analysis*

During this phase, the most recent remotely sensed images are analysed, and some preliminary GIS analysis is performed. For example, the boundaries of the river corridor (in the case of an unconfined or partly confined reach) and the channel margins are identified, and some indicators can undergo preliminary assessment or some tentative hypothesis can be made before the field survey (e.g., bank erosion, potentially erodible corridor, planform pattern, width and linear extension of functional vegetation, etc.). This will aid in identifying critical points and prioritising locations to visit during the field survey (see next step). Measurement of channel width in contemporary and historical conditions (the latter evaluated only in the case of sufficiently large rivers) can already be carried out during this phase: this may require georeferencing aerial photos and digitising channel margins. During this and the following phase, the hard copy of the *Evaluation Forms* can be used.

*3. Field survey*

It is important, if the results of the field survey are to be optimized, that it addresses and checks the critical aspects identified during the previous phase. Furthermore, this phase is strictly necessary for a series of indicators requiring field observation and/or measurement (e.g., presence and extension of a modern floodplain, structure of the channel bed, presence of in-channel large wood, etc.). If a map layer of interventions is available, this will facilitate and minimize the field work. Therefore, the field survey should possibly be preceded by a detailed plan of the areas to be visited.

*4. Concluding GIS analysis*

Once the critical aspects of the evaluation have been solved by means of the field survey, the GIS analysis and the measurement of quantitative parameters can now be finalised during this final phase. As well as completing the hard copy of the *Evaluation Forms*, the electronic format can be compiled during this final phase.

Some additional aspects to be considered during the application for the MQI are the following.

*Period of the year for carrying out the field survey*
There are no specific requirements or constraints on the time of year to carry out the field survey. The only recommendation is to avoid periods of high flow events, for obvious safety reasons, and because this would create unfavourable conditions for carrying out field observations, as most of the channel bed would be submerged. Indeed, during excessively low flow (eventually dry) periods, the assessment is not precluded. It is important to note that the assessment concerns the entire stream channel and river corridor, and not only its submerged portion.

*Time interval of the MQI assessment*
It is important to note that the channel delimitation is carried out using the most recent remote sensing images selected for the MQI application. During the execution of the field survey, some channel modification due to erosion or deposition may be observed (this is very likely the case in dynamic streams). In such a case, however, the operator will not make any modification to the channel boundaries (or other natural elements) because these are not relevant for the MQI result. The evaluation of indicators based on GIS measurements is therefore referred to the date of the remote sensing images. Field observations, however, are used to verify and integrate those aspects which cannot be determined by remote sensing, further to evaluating those indicators which can be exclusively assessed in the field. Concerning artificiality, field observations can eventually add some updated information regarding interventions that was not available from existing map layers. These need to be considered since they are relevant for the MQI result.
In summary, the MQI assessment cannot be referred to a precise date (given that it is not a field sampling method), but it refers, rather, to an interval of time ranging from the date of the images used for the analysis and the date of the field survey.

**Time required for the application of the MQI**

As previously emphasised, the MQI is not just a field sampling methodology and so cannot be realised in only a few hours of field work. Quantification of the time required for the application of the MQI is not straightforward as it depends on a series of factors, mainly: (i) the competence, training level, and experience of the operator; (ii) the availability of data and other information (e.g., the existence of a map layer of interventions and management practices will significantly reduce the time). The time required for an application to a single reach also depends on the number of reaches of the same segment or river being assessed. Application to various reaches will generally optimise the work and reduce the unit time required for each reach: some steps carried out for the whole segment/river may require about the same time as for each single reach. In reference to the four working phases described earlier, the following considerations can be made:

*1. Collection of existing material*. This is extremely variable and depends considerably on the data and material availability before starting the assessment. In some cases, all the material is already available and only a small amount of time is required. Should the reach delineation need to be carried out, this will significantly increase the required time, as some parameters (confinement degree, sinuosity index, etc.) need to be measured to define the confinement class and the river typology.

*2. Preliminary remote sensing - GIS analysis*. Depending on channel type and sizes (for example, small confined streams vs. large unconfined rivers) this phase can require a time approximately ranging from a few hours to one day.

*3. Field survey*. Time required for the field survey is maximum one day. This may be reduced (to a minimum of half a day, i.e. two reaches per day) in the case of simple, relatively uniform reaches.

*4. Concluding GIS analysis*. This phase is also variable, depending on the complexity or uniformity of the reach, but a maximum of one day can be assumed to precisely quantify all the variables required to estimate the indicators, also allowing for the application of the MQIm.

### 1.8.3 Ranges of application

The MQI evaluation can be applied to <u>any stream</u>. The following ranges of application and/or limitations can be considered:
- It can also be applied to a reach close to the mouth, i.e. where the channel is well delimitated by riverbanks.
- It can be applied to strongly artificial reaches, e.g. partially or completely fixed reaches in urban areas.
- Conversely, it is not applicable to artificial water bodies, lakes, or reservoirs.

# 2. The Morphological Quality Index for monitoring (MQIm)

## *2.1 Introduction*

The Morphological Quality Index (MQI) was mainly designed to assess the overall current morphological conditions of a stream reach (i.e., a relatively homogeneous portion of the river with a length of the order of some km), reflecting alterations over a long time scale. Therefore, the MQI may not be suitable for monitoring changes of channel conditions occurring in a short period of time and/or in small portions of the reach (e.g., due to the removal of a bank protection structure).

To address this limitation, a new index, named Morphological Quality Index for monitoring (MQIm), has specifically been designed to take into account small changes (e.g. relative to small portions of a reach) and short time scales (i.e., a few years). Therefore, MQIm is particularly suitable for the environmental impact assessment of interventions, including both flood mitigation and restoration actions.

This section aims to present this new tool and to show typical ranges of application in river monitoring, management and restoration.

## *2.2 Characteristics of the MQIm and differences with the MQI*

The need to adopt a new procedure for monitoring morphological quality derives from the investigated spatial and temporal scales, which are different from the previous phase of assessment and classification of the current morphological state. Concerning the temporal scale, the MQI evaluates the overall morphological current conditions deriving from modifications which have occurred over the last 50-100 years. The MQIm is a specific tool for monitoring changes in morphological quality over a time scale of a few years, for example after the implementation of an intervention which could have enhanced or deteriorated the morphological conditions.

The main differences between MQI and MQIm are summarised in Table 2.1 and briefly reported as follows:

(1) The MQI is a tool for the evaluation, classification, and monitoring of the *morphological state* (i.e., good, poor, etc.). The MQIm is a tool for specifically monitoring morphological conditions in the short term, i.e. to evaluate the *tendency of morphological conditions* (enhancement or deterioration).

(2) The MQI scores are based on *discrete classes*, whereas the scores of many MQIm indicators are based on *continuous mathematical functions*.

(3) As a consequence of the previous point, MQIm is more sensitive to changes occurring at a *temporal scale of a few years*.

(4) Although the MQI *indicators of channel adjustments* (*CA1*, *CA2*, and *CA3*) should be monitored, they are not explicitly included in the calculation of the MQIm. This is because channel adjustments which occurred in the past are necessary for evaluating channel instability in the MQI, whereas a recent, short term change cannot be interpreted and quantified with the same criterion. In fact, current trends of adjustment must be set in the context of the evolutionary trajectory of changes and cannot easily be quantified for the scope of the MQIm calculation. Channel adjustments are however indirectly taken into account by some of the indicators of functionality. For example, in the case of a river reach changing from single-thread to braided as a response to bank protection removal, adjustment of channel pattern is not quantified by the indicator *CA1* in the MQIm, but the geomorphological functionality (e.g., indicator *F7*) must be interpreted accounting for this adjustment towards more natural conditions.

**Table 2.1 Main differences between *MQI* and *MQIm.***

| | Aim | Temporal scale | Scores | Applications |
|---|---|---|---|---|
| **MQI** | Assessment, classification and monitoring of the current morphological state | 50 – 100 years | Discrete classes | Tool to evaluate morphological alterations compared to undisturbed conditions |
| **MQIm** | Monitoring of morphological conditions in the short term | 5 – 10 years | Continuous functions and discrete classes | Tool to evaluate changes of morphological quality in the short term |

## *2.3 Scoring system and mathematical functions*

Indicators based on presence/absence criteria and/or predominantly based on field observations and interpretations are maintained in the format used for MQI, whereas a series of mathematical functions are defined for those indicators based on quantitative parameters (e.g., percentage of altered reach, number of artificial structures, etc.) (Table 2.2).

**Table 2.2 List of indicators for which the scores are defined by mathematical functions*.***

| Functionality | Artificiality |
|---|---|
| *F2, F3, F5, F6, F7, F9, F12, F13* | *A2, A4, A5, A6, A7, A8, A9, A12* |

Mathematical functions for the indicators reported in Table 2.2 have been defined on the basis of the following criteria (Figure 2.1):
(1) Linear "upper" and "lower" interpolating functions are first defined, based on the histogram of discrete classes used for the MQI.
(2) The MQIm function is obtained by a series of segments equidistant from the upper and lower interpolating functions. Concerning the last discrete class (on the right of Fig. 2.1), a segment parallel to the lower interpolating function is assumed.

Similarly to the MQI, the Morphological Quality Index for monitoring (MQIm) is defined as

$$\text{MQIm} = 1 - \text{Stot}/\text{Smax} \qquad (2)$$

where Stot is the sum of the scores, and Smax is the maximum score that could be reached when all indicators assume the maximum possible score. Note that the possible maximum score for each indicator is higher than in the case of MQI, as can be observed in Figure 2.1, therefore Smax is also higher. This implies that the values of MQI and MQIm are not directly comparable.

For the application of the MQIm, it is possible to use the same field **evaluation forms** as for the MQI by using the space below the indicators with mathematical functions to report the specific values of the parameters needed for the calculation of the indicator. Then, the electronic format of the MQIm evaluation forms is available at http://wiki.reformrivers.eu, allowing automatic calculation of the indicators once the input values have been typed in.

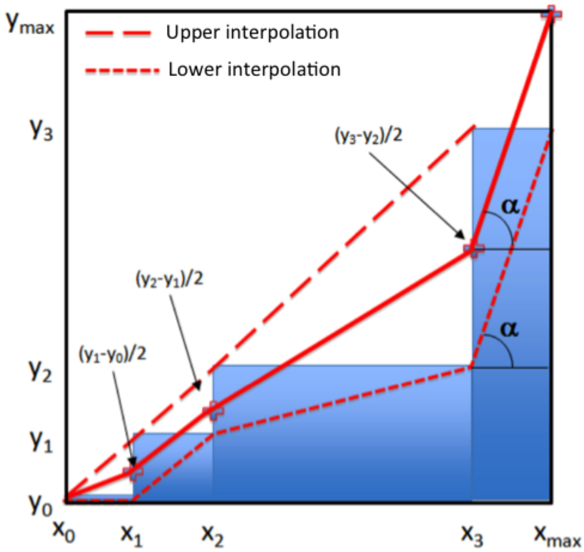



**Figure 2.1 Procedure for the definition of the mathematical functions of a MQIm indicator deriving from the discrete classes of the same MQI indicator.**

## *2.4 Evaluation procedures, limitations and applications*

The MQI and MQIm evaluate morphological quality at a different temporal scale, therefore they can be considered as complementary rather than alternative assessments. The MQIm provides an indication on the *trend of morphological quality* in the short term. To this end, the value of MQIm related to a single situation is not meaningful, but the difference of the index between two assessments is particularly relevant, indicating a *tendency to an enhancement or deterioration* of the morphological quality.

For the previous reasons, it is important to integrate the MQIm assessment with a new evaluation of the MQI, thus providing information on a possible change in the overall state of the reach, further to its tendency. To this end, note that the new calculation of MQI will be available once all the information for the MQIm is available, with the sole addition of the indicators of channel adjustments.

For the application of both the MQI and MQIm, the following two specific cases require particular caution:
(1) *River restoration interventions*. In the case of the implementation of a restoration project involving a significant portion of the reach, it is advisable to conduct the assessment some time after the intervention, for example after some formative flood event. In any case, a period of at least 5 years subsequent to the intervention in advisable. This is particularly true in the case of interventions of "morphological reconstruction", in which case it is necessary for the river to be able to adapt to the new conditions.
(2) *Large flood events*. In the case of the occurrence of a flood event of high intensity (e.g., flood with a return period > 10-20 years), particular attention must be paid to the interpretation of any eventual morphological changes. In fact, the effects of such events could strongly influence the interpretation of forms and processes. In such cases, the application of the MQI and MQIm some years after the occurrence of the flood is advisable.

Some main *applications* of the MQIm for monitoring morphological conditions are as follows:
(1) *WFD monitoring*. The MQIm can be adopted, in integration with the MQI, for the WFD monitoring, with a spatio-temporal frequency that can be defined depending on the the type of monitoring (surveillance, operative, investigative).

(2) *Evaluation of the impact of new interventions*. The MQIm is particularly suitable for evaluating the possible impacts of an intervention (including river restoration projects) during the design stage given that this index is sensitive to the impact of interventions even of a limited length compared to the reach length. To this purpose, an *ante operam* assessment, evaluating the current conditions, can be followed by a *post operam* assessment, making assumptions concerning the expected changes in some of the morphological indicators in response to the intervention. The comparison of *ante* and *post operam* assessment will indicate the tendency to improvement or deterioration of the project.

# References

Belletti, B., Rinaldi, M., Gurnell, A.M., Buijse, A.D., Mosselman, E., 2015. A review of methods for river hydromorphological assessment. Environmental Earth Sciences, doi: 10.1007/s12665-014-3558-1.

Brierley, G.J., Fryirs, K.A., 2005. Geomorphology and River Management: Applications of the River Style Framework. Blackwell, Oxford, UK, 398 pp.

Comité Européen de Normalisation (CEN), 2002. A Guidance Standard for Assessing the Hydromorphological Features of Rivers. European Committee for Standardization, EN 14614, Brussels, Belgium, 24 pp.

Chandesris, A., Mengin, N., Malavoi, J.R., Souchon, Y., Pella, H., Wasson, J.G., 2008. Systeme Relationnel d'Audit de l'Hydromorphologie des Cours d'Eau. Principes et methodes, v3.1. Cemagref, Lyon Cedex, 81 pp.

European Commission, 2003. Rivers and Lakes – Typologies, Reference Conditions and Classification Systems. Common Implementation Strategy for the Water Framework Directive (2000/60/EC), Guidance document n°10, Brussels, Belgium, 87 pp.

Florsheim, J.L., Mount, J.F., Chin, A., 2008. Bank erosion as a desirable attribute of rivers. Bioscience 58(6), 519-529.

Fryirs, K.A., Arthington, A., Grove, J., 2008. Principles of river condition assessment. In: Brierley, G., Fryirs, K.A. (Eds.), River Futures: An Integrative Scientific Approach to River Repair. Society for Ecological Restoration International, Island Press, Washington, DC, USA, pp. 100-124.

Habersack, H., Piégay, H., 2008. River restoration in the Alps and their surroundings: past experience and future challenges. In: Habersack, H., Piégay, H., Rinaldi, M. (Eds.), Gravel-bed Rivers VI - From Process Understanding to River Restoration. Developments in Earth Surface Processes, Elsevier, Amsterdam, The Netherlands, pp. 703-738.

Gurnell, A.M., Bussettini, M., Camenen, B., González Del Tánago, M., Grabowski, R.C., Hendriks, D., Henshaw, A., Latapie, A., Rinaldi, M., Surian, N., 2014a. A multi-scale framework and indicators of hydromorphological processes and forms. Deliverable 2.1, Part 1, of REFORM (REstoring rivers FOR effective catchment Management), a Collaborative project (large-scale integrating project) funded by the European Commission within the 7th Framework Programme under Grant Agreement 282656.

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

ISPRA, 2009. Implementazione della Direttiva 2000/60/CE - Analisi e valutazione degli aspetti idromorfologici. http://www.sintai.sinanet.apat.it/view/index.faces.

Kondolf, G.M., 1995. Geomorphological stream classification in aquatic habitat restoration: uses and limitations. Aquatic Conservation: Marine and Freshwater Ecosystems 5, 127-141.

Kondolf, G.M., Montgomery, D., Piégay, H., Schmitt, L., 2003a. Geomorphic classifications of rivers and streams. In: Kondolf, G.M., Piégay, H. (Eds.), Tools in Fluvial Geomorphology. John Wiley and Sons, Chichester, UK, pp. 171-204.

Kondolf, G.M., Piégay, H., Sear, D., 2003b. Integrating geomorphological tools in ecological and management studies. In: Kondolf, G.M., Piégay, H. (Eds.), Tools in Fluvial Geomorphology. John Wiley and Sons, Chichester, UK, pp. 633-660.

LAWA, 2000. Gewässerstrukturgütebewertung in der Bundesrepublik Deutschlan. Verfahren für kleine und mittelgroße Fließgewässer, Berlin.

Leopold, L.B., Wolman, M.G., 1957. River channel patterns: braided, meandering and straight. US.Geol.Surv., Prof.Paper, 282-B, 39-85.

Liébault, F., Piégay, H., 2002. Causes of 20th century channel narrowing in mountain and piedmont rivers of southeastern France. Earth Surf Proc Land 27, 425-444.

Montgomery, D.R., Buffington, J.M., 1997. Channel-reach morphology in mountain drainage basins. Geological Society of America Bulletin, 109 (5), 596-611.

Ollero, O.A., Ballarín, F.D., Díaz, B.E., Mora, M.D., Sánchez, F.M., Acín, N.V., Echeverría, A.M.T., Granado, G.D., Ibisate, G.A., Sánchez, G.L., Sánchez, G.N., 2007. Un indice hydrogeomorfologico (IHG) para la evaluacion del estado ecologico de sistemas fluviales. Geographicalia 52, 113-141.

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

Piégay, H., Darby, S.E., Mosselman, E., Surian, N., 2005. A review of techniques available for delimiting the erodible river corridor: a sustainable approach to managing bank erosion. River Research and Applications, 21, 773-789.

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E., Stromberg, J.C., 1997. The natural flow regime: a new paradigm for riverine conservation and restoration. BioScience, 47(11), 769-784.

Raven, P.J., Fox, P.J.A., Everard, M., Holmes, N.T.H., Dawson, F.H., 1997. River habitat survey: a new system for classifying rivers according to their habitat quality. In: Boon, P.J., Howell, D.L. (Eds.), Freshwater Quality: Defining the Indefinable? Scottish Natural Heritage, The Stationery Office, Edinburg, Scotland, pp. 215-234.

Richter, B.D., Baumgartner, J.V., Powell, J., Braun, D.P. 1996. A Method for Assessing Hydrologic Alteration within Ecosystems. Conservation Biology, 10(4), 1163-1174.

Rinaldi, M., Simon, A., 1998. Bed-level adjustments in the Arno River, central Italy. Geomorphology 22, 57-71.

Rinaldi, M., Surian, N., Comiti, F., Bussettini, M., 2012. Guidebook for the evaluation of stream morphological conditions by the Morphological Quality Index (MQI). Version 1.1, ISPRA, Rome, September 2012, http://www.isprambiente.gov.it/en/publications/handbooks-and-guidelines/guidebook-for-the-evaluation-of-stream-1.

Rinaldi, M., Surian, N., Comiti, F., Bussettini, M., 2013. A method for the assessment and analysis of the hydromorphological condition of Italian streams: the Morphological Quality Index (MQI). Geomorphology, doi: 10.1016/j.geomorph.2012.09.009, 180-181, 96-108.

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

Sneath, P.H.A., Snokal, R.R., 1973. Numerical Taxonomy: The Principles and Practice of Numerical Classification. W.H. Freeman, San Francisco, CA, USA, 573 pp.

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

Surian, N., Rinaldi, M., Pellegrini, L., Audisio, C., Maraga, F., Teruggi, L.B., Turitto, O., Ziliani, L., 2009. Channel adjustments in northern and central Italy over the last 200 years. In: James, L.A., Rathburn, S.L., Whittecar, G.R. (Eds.), Management and Restoration of Fluvial Systems with Broad Historical Changes and Human Impacts. Geological Society of America Special Paper 451, Boulder, CO, USA, pp. 83-95.

Wohl, E., Angermeier, P.L., Bledsoe, B., Kondolf, G.M., McDonnell, L., Merritt, D.M., Palmer, M.A., Poff, L., Tarboton, T., 2005. River Restoration, Water Resources Research 41, W10301, doi: 10.1029/2005WR003985.

Wyżga, B., Zawiejska, J., Radecki-Pawlik, A., Amirowicx, A., 2010. A method for the assessment of hydromorphological river quality and its application to the Czarny Dunajec, Polish Carpathians. In: Radecki-Pawlik, A., Hernik, J. (Eds.), Cultural Landscapes of River Valleys. Agricultural University in Kraków, Kraków, Poland, pp. 145-164.

Wyżga, B., Zawiejska, J., Radecki-Pawlik, A., Hajdukiewicz, H., 2012. Environmental change, hydromorphological reference conditions and the restoration of Polish Carpathian rivers. Earth Surface Processes and Landforms, DOI: 10.1002/esp.3273.

# Appendix 1: Evaluation Form for Confined Channels

# *Morphological Quality Index (MQI)*

## EVALUATION FORMS FOR CONFINED CHANNELS

*Version 1 - October 2015*

### GENERALITY

Date ____________ Operators ____________
Catchment ____________ Stream/river ____________
Upstream limit ____________ Downstream limit ____________
Segment code ________ Reach Code ________ Reach length (m) ________

### DELINEATION OF SPATIAL UNITS

**1. Physiographic setting**

Physiographic context ____ *M*=Mountains, *H*=Hills Landscape unit ____________

**2. Confinement**

Confinement degree (%) ______ >90, 10-90 Confinement index ______ (1-1.5)

**3. Channel morphology**

Aerial photo or satellite image ____________ (name, year)
Channel type ______ *ST*=single-thread, *MT/W*=multi-thread or wandering

*Confined single-thread (S-T):*

Bed configuration ______ *BR*=Bedrock, *CO*=Colluvial, *C*=Cascade, *SP*=Step Pool, *PB*=Plane bed, *RP*=Riffle Pool, *DR*=Dune ripple, *A*= Artificial, *NC*= not classified (high depth or strong alteration)

*Confined multi-thread or wandering (M-T/W):*

Braiding index ______ 1-1.5, >1.5 Anabranching index ______ 1-1.5, >1.5
Tipology ______ *W*= wandering, *B*= Braided, *A*= Anabranching
Mean bed slope, *S* ______ Mean channel width, *W* (m) ______
Bed sediment (dominant) ____ *C*=Clay, *Si*=Silt, *Sa*=Sand, *G*=Gravel, *C*=Cobbles, *B*=Boulders

**4. Other elements for reach delineation**

Upstream ____________ Downstream ____________
change in geomorphic units, bed slope discontinuity, tributary, dam, artificial elements, change in confinement and/or size of the floodplain, changes in grain size, other (specify) ____________

**Additional available data / information**

Drainage area (at the downstream limit) (km$^2$) ________
Sediment size, $D_{50}$ (mm) ______ Unit ______ *Be*=Bed, *Ba*=Bar (*SU*=surface layer, *SUB*=sublayer)
Discharges ______ *M*=measured, E=estimated, *NA*=not available
Gauging station (if *M*) ________ Mean annual discharge (m$^3$/s) ______ $Q_{1.5}$ or $Q_2$ (m$^3$/s) ______
Maximum discharges (indicate year and *Q* when known) ____________

### GEOMORPHOLOGICAL FUNCTIONALITY

**Continuity**

| | | part. | prog. | conf. |
|---|---|---|---|---|
| **F1** | **Longitudinal continuity in sediment and wood flux** | | | |
| A | Absence of alteration in the continuity of sediment and wood | 0 | | |
| B | Slight alteration (obstacles to the flux but with no interception) | 3 | | |
| C | Strong alteration (discontinuity of channel forms and interception of sediment and wood) | 5 | | |

| | | part. | prog. | conf. |
|---|---|---|---|---|
| **F3** | **Hillslope - river corridor connectivity** | | | |
| A | Full connectivity between hillslopes and river corridor (>90%) | 0 | | |
| B | Connectivity for a significant portion of the reach (33÷90%) | 3 | | |
| C | Connectivity for a small portion of the reach (≤33%) | 5 | | |

*part.*: partial scores (to circle) *prog.*: progressive scores *confidence level between A and B*
*conf.*confidence level in the answer, with *M*=Medium, *L*=Low *(High is omitted)* *confidence level between B and C*

# *Morphological Quality Index (MQI)*

## Morphology

*Morphological pattern*

| F6 | **Bed configuration - valley slope** *(applied to S-T channels)* | | |
|---|---|---|---|
| A | Bed forms consistent with the mean valley slope or not consistent for ≤33% of the reach | 0 | |
| B | Bed forms not consistent with the mean valley slope for 33-66% of the reach | 3 | |
| C | Alteration of bed forms for >66% of the reach | 5 | |

*Not evaluated for bedrock streams, and for deep streams when it is not possible to observe the channel bed*

| F7 | **Planform pattern** *(applied to M-T or W channels)* | | |
|---|---|---|---|
| A | Absence (<5%) of alteration of the natural heterogeneity of geomorphic units and channel width | 0 | |
| B | Alterations for a limited portion of the reach (≤33%) | 3 | |
| C | Consistent alterations for a significant portion of the reach (>33%) | 5 | |

*Cross-section configuration*

| F9 | **Variability of the cross-section** | | |
|---|---|---|---|
| A | Absence (≤5%) of alteration of the cross-section natural heterogeneity (channel depth/velocity) | 0 | |
| B | Presence of alteration (cross-section homogeneity) for a limited portion of the reach (≤33%) | 3 | |
| C | Presence of alteration (cross-section homogeneity) for a significant portion of the reach (>33%) | 5 | |

*Bed structure and substrate*

| F10 | **Structure of the channel bed** | | |
|---|---|---|---|
| A | Natural heterogeneity of bed sediments and no significant clogging | 0 | |
| B | Evident clogging for ≤50% of the reach | 2 | |
| C1 | Evident clogging for >50% of the reach or occasional substrate outcrops (≤ 33% of the reach) related to recent bed-incision of the alluvial substrate | 5 | |
| C2 | Widespread alteration of substrate due to bed revetment or substrate outcrops (>33% of the reach) | 6 | |

*Not evaluated for sand-bed or bedrock streams, and for deep streams when it is not possible to observe the channel bed*

| F11 | **Presence of in-channel large wood** | | |
|---|---|---|---|
| A | Significant presence of large wood along the whole reach (or "wood transport" reach) | 0 | |
| B | Negligible presence of large wood for ≤50% of the reach | 2 | |
| C | Negligible presence of large wood for >50% of the reach | 3 | |

*Not evaluated above the tree-line and in streams with natural absence of riparian vegetation (e.g. north-European tundra)*

## Vegetation in the fluvial corridor

| F12 | **Width of functional vegetation** | | |
|---|---|---|---|
| A | High width of functional vegetation | 0 | |
| B | Medium width of functional vegetation | 2 | |
| C | Low width of functional vegetation | 3 | |

*Not evaluated above the tree-line and in streams with natural absence of riparian vegetation (e.g. north-European tundra)*

| F13 | **Linear extension of functional vegetation and presence of emergent aquatic macrophytes** | | |
|---|---|---|---|
| A | Riparian vegetation >90% of maximum length, or riparian vegetation>33% and significant presence of emergent aquatic vegetation (low-energy channels) | 0 | |
| B | Riparian vegetation 33÷90%, or riparian vegetation >90% but very limited presence of aquatic vegetation, or riparian vegetation ≤33% but significant presence of aquatic vegetation | 3 | |
| C | Riparian vegetation ≤33%, or <90% but very limited presence of aquatic vegetation | 5 | |

*Riparian vegetation not evaluated above the tree-line and in streams with natural absence (e.g. north-European tundra)*
*Aquatic vegetation evaluated only in low-energy single-thread or anabranching channels*

# *Morphological Quality Index (MQI)*

## ARTIFICIALITY

### Upstream alteration of longitudinal continuity

| | | part. | prog. | conf. |
|---|---|---|---|---|
| **A1** | **Upstream alteration of flows** | | | |
| A | No significant alteration (≤10%) of channel-forming discharges and with return interval>10 years | 0 | | |
| B | Significant alteration (>10%) of discharges with return interval>10 years or release of increased low flows downstream dams during dry seasons | 3 | | |
| C | Significant alteration (>10%) of channel-forming discharges | 6 | | |

| | | | | |
|---|---|---|---|---|
| **A2** | **Upstream alteration of sediment discharges** | | | |
| 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 | | |
| B1 | Dams (area 5-33%) and/or check dams/weirs with total bedload interception (area 33-66%) and/or check dams/weirs with partial or no interception (area>66%) | 3 | | |
| B2 | Dams (area 33-66%) and/or check dams/weirs with total bedload interception (area>66%) | 6 | | |
| C1 | Dams for drainage area >66% | 9 | | |
| C2 | Dam at the upstream boundary of the reach | 12 | | |

### Alteration of longitudinal continuity in the reach

| | | | | |
|---|---|---|---|---|
| **A3** | **Alteration of flows in the reach** | | | |
| A | No significant alteration (≤10%) of channel-forming discharges and with return interval>10 years | 0 | | |
| B | Significant alteration (>10%) of discharges with return interval>10 years | 3 | | |
| C | Significant alteration (>10%) of channel-forming discharges | 6 | | |

| | | | | |
|---|---|---|---|---|
| **A4** | **Alteration of sediment discharge in the reach** | | | |
| A | Absence of structures for the interception of sediment fluxes (dams, check dams, abstraction weirs) | 0 | | |
| B | *Channels with S≤1%:* consolidation check dams and/or abstraction weirs ≤1 every 1000 m<br>*Steep channels (S>1%):* consolidation check dams ≤1 every 200 m and/or open check dams | 4 | | |
| C | *Channels with S≤1%:* consolidation check dams and/or abstraction weirs >1 every 1000 m<br>*Steep channels (S>1%):* consolidation check dams >1 every 200 m and/or retention check dams<br>Or presence of a dam or artificial reservoir at the downstream boundary (*any bed slope*) | 6 | | |
| | *In case of density of interception structures, including bed sills and ramps (see A9), is >1 every d1, add* | 6 | | |
| | *In case of density of interception structures, including bed sills and ramps (see A9), is >1 every d2, add* | 12 | | |
| | *where d1=150 m and d2=100 m in steep channels, or d1=750 m and d2=500 m in channels with S≤1%* | | | |

| | | | | |
|---|---|---|---|---|
| **A5** | **Crossing structures** | | | |
| A | Absence of crossing structures (bridges, fords, culverts) | 0 | | |
| B | Presence of some crossing structure (≤1 every 1000 m in average in the reach) | 2 | | |
| C | Presence of many crossing structure (>1 every 1000 m in average in the reach) | 3 | | |

### Alteration of lateral continuity

| | | | | |
|---|---|---|---|---|
| **A6** | **Bank protections** | | | |
| A | Absence or localized presence of bank protections (≤5% total length of the banks) | 0 | | |
| B | Presence of protections for ≤33% total length of the banks (sum of both banks) | 3 | | |
| C | Presence of protections for >33% total length of the banks (sum of both banks) | 6 | | |
| | *In case of high density of bank protection (>50%) add* | 6 | | |
| | *In case of extremely high density of bank protection (>80%) add* | 12 | | |

### Alteration of channel morphology and/or substrate

| | | | | |
|---|---|---|---|---|
| **A9** | **Other bed stabilization structures** | | | |
| A | Absence of structures (bed sills/ramps) and revetments absent or localised (≤5%) | 0 | | |
| B | Sills or ramps (≤1 every *d*) and/or revetments ≤25% permeable and/or ≤15% impermeable | 3 | | |
| C1 | Sills or ramps (>1 every *d*) and/or revetments ≤50% permeable and/or ≤33% impermeable | 6 | | |
| C2 | Revetments >50% permeable and/or >33% impermeable | 8 | | |
| | *d=200 m in steep channels (S>1%); d= 1000 m in channels with S≤1%* | | | |
| | *In case of high density of bed revetment (impermeable >50% or permeable >80%) add* | 6 | | |
| | *In case of extremely high density of bed revetment (impermeable >80%) add* | 12 | | |

# *Morphological Quality Index (MQI)*

**Intervention of maintenance and removal**

| **A10** | **Sediment removal** | | |
|---|---|---|---|
| A | Absence of significant sediment removal activities during the last 20 years | 0 | |
| B | Localized sediment removal activities during the last 20 years | 3 | |
| C | Widespread sediment removal activities during the last 20 years | 6 | |

*Not evaluated in the case of bedrock streams*

| **A11** | **Wood removal** | | |
|---|---|---|---|
| A | Absence of removal of woody material at least during the last 20 years | 0 | |
| B | Partial removal of woody material during the last 20 years | 2 | |
| C | Total removal of woody material during the last 20 years | 5 | |

*Not evaluated above the tree-line and in streams with natural absence of riparian vegetation (e.g. north-European tundra)*

| **A12** | **Vegetation management** | | |
|---|---|---|---|
| A | No cutting interventions on riparian (last 20 years) and aquatic vegetation (last 5 years) | 0 | |
| B | Selective cuts and/or clear cuts of riparian vegetation ≤50% of the reach and partial or no cutting of aquatic vegetation, or no cutting of riparian but partial or total cutting of aquatic vegetation | 2 | |
| C | Clear cuts of riparian vegetation >50% of the reach, or selective cuts and/or clear cuts of riparian vegetation ≤50% of the reach but total cutting of aquatic vegetation | 5 | |

*Riparian vegetation not evaluated above the tree-line and in streams with natural absence (e.g. north-European tundra)*
*Aquatic vegetation evaluated only in low-energy single-thread or anabranching channels*

**CHANNEL ADJUSTMENTS**

| | | | *part.* | *prog.* | *conf.* |
|---|---|---|---|---|---|
| **CA1** | **Adjustments in channel pattern** | | | | |
| A | Absence of change of channel pattern from 1930s - 1960s | 0 | | | |
| B | Change of channel pattern from 1930s - 1960s | 3 | | | |

*Not evaluated in the case of small streams where resolution of aerial photos is insufficient*

| **CA2** | **Adjustments in channel width** | | |
|---|---|---|---|
| A | Absent or limited changes in channel width (≤15%) from 1930s - 1960s | 0 | |
| B | Changes in channel width >15% from 1930s - 1960s | 3 | |

*Not evaluated in the case of small streams where resolution of aerial photos is insufficient*

| **CA3** | **Bed-level adjustments** | | |
|---|---|---|---|
| A | Negligible bed-level changes (≤0.5 m) | 0 | |
| B | Limited to moderate bed-level changes (0.5÷3 m) | 4 | |
| C | Intense bed-level changes (>3 m) | 8 | |

*Not evaluated in the case of absolute lack of data, information and field evidence*

**Total deviation:** ***Stot =***

**Maximum deviation:** ***Smax* = 119 - *Sna*=**

*where Sna = sum of maximum scores for indicators that have not been applied*

**Morphological Alteration Index:** ***MAI = Stot / Smax =***

*if Stot>Smax, MAI is assumed =1*

**Morphological Quality Index:** ***MQI=1-MAI =***

**Quality class of the reach**

0≤*MQI*<0.3: Very Poor or Bad; 0.3≤*MQI*<0.5: Poor; 0.5≤*MQI*<0.7: Moderate;
0.7≤*MQI*<0.85: Good; 0.85≤*MQI*≤1.0: Very Good or High

# Appendix 2: Evaluation Form for Partly Confined or Unconfined Channels

# *Morphological Quality Index (MQI)*

## EVALUATION FORMS FOR PARTLY CONFINED AND UNCONFINED CHANNELS

*Version 1 - October 2015*

### GENERALITY

Date ______________ Operators ______________

Catchment ______________ Stream/river ______________

Upstream limit ______________ Downstream limit ______________

Segment code ________ Reach Code ________ Reach length (m) ________

### DELINEATION OF SPATIAL UNITS

**1. Physiographic setting**

Physiographic context ____ *M*=Mountains, *H*=Hills, *P*=Plain Landscape unit ______________

**2. Confinement**

Confinement degree (%) ________ >90, 10-90, ≤10

Confinement index ________ 1-1.5, 1.5-*n*, >*n* *(n=5 single-thread or anabranching; n=2 braided or wandering)*

Confinement class ________ *PC*=Partly confined, *U*=Unconfined

**3. Channel morphology**

Aerial photo or satellite image ______________ (name, year)

Sinuosity index ________ 1-1.05, 1.05-1.5, >1.5

Braiding index ________ 1-1.5, >1.5 Anabranching index ________ 1-1.5, >1.5

Typology ________ *ST*=Straight*, S*=Sinuous*, M*=Meandering*, W*= Wandering, *B*= Braided, *A*= Anabranching

Bed configuration ________ *BR*=bedrock, *C*=Cascade, *SP*=Step Pool, *PB*=Plane bed, *RP*=Riffle Pool, *DR*=Dune ripple

(only for single-thread channels) *A*= Artificial, *NC*= not classified (high depth or strong alteration)

Mean bed slope, *S* ________ Mean channel width, *W* (m) ________

Bed sediment (dominant) ____ *C*=Clay, *Si*=Silt, *Sa*=Sand, *G*=Gravel, *C*=Cobbles, *B*=Boulders

**4. Other elements for reach delineation**

Upstream ______________ Downstream ______________

change in geomorphic units, bed slope discontinuity, tributary, dam, artificial elements, change in confinement and/or size of the floodplain, changes in grain size, other (specify) ______________

**Additional available data / information**

Drainage area (at the downstream limit) ($km^2$) ________

Sediment size, $D_{50}$ (mm) ________ Unit ________ *Be*=Bed, *Ba*=Bar (*SU*=surface layer, *SUB*=sublayer)

Discharges ________ *M*=measured, E=estimated, *NA*=not available

Gauging station (if *M*) ________ Mean annual discharge ($m^3/s$) ________ $Q_{1.5}$ or $Q_2$ ($m^3/s$) ________

Maximum discharges (indicate year and *Q* when known) ______________

### GEOMORPHOLOGICAL FUNCTIONALITY

**Continuity**

| | | part. | prog. | conf. |
|---|---|---|---|---|
| **F1** | **Longitudinal continuity in sediment and wood flux** | | | |
| A | Absence of alteration in the continuity of sediment and wood | 0 | | |
| B | Slight alteration (obstacles to the flux but with no interception) | 3 | | |
| C | Strong alteration (discontinuity of channel forms and interception of sediment and wood) | 5 | | |

| | | part. | prog. | conf. |
|---|---|---|---|---|
| **F2** | **Presence of a modern floodplain** | | | |
| A | Presence of a continuous (>66% of the reach) and wide modern floodplain | 0 | | |
| B1 | Presence of a discontinuous (10÷66%) but wide modern floodplain or >66% but narrow | 2 | | |
| B2 | Presence of a discontinuous (10÷66%) and narrow modern floodplain | 3 | | |
| C | Absence of a modern floodplain or negligible presence (≤10% of any width) | 5 | | |

*Not evaluated in the case of mountain streams along steep (>3%) alluvial fans*

*part.*: partial scores (to circle) *prog.*: progressive scores *confidence level between A and B*

*conf.*confidence level in the answer, with *M*=Medium, *L*=Low *(High is omitted)* *confidence level between B and C*

# *Morphological Quality Index (MQI)*

| F4 | Processes of bank retreat | | |
|---|---|---|---|
| A | Bank erosion occurs for >10% and is distributed along >33% of the reach | 0 | |
| B | Bank erosion occurs for ≤10%, or for >10% but is concentrated along ≤33% of the reach or significant presence (>25%) of eroding banks by mass failures | 2 | |
| C | Complete absence (≤2%) or widespread presence (>50%) of eroding banks by mass failures | 3 | |

*Not evaluated in the case of low energy straight, sinuous and anabranching channels and groundwater-fed streams*

| F5 | Presence of a potentially erodible corridor | | |
|---|---|---|---|
| A | Presence of a wide potentially erodible corridor (EC) for a length >66% of the reach | 0 | |
| B | Presence of a narrow potentially EC for >66%, or wide but for 33-66% of the reach | 2 | |
| C | Presence of a potentially EC of any width but for ≤33% of the reach | 3 | |

**Morphology**

*Morphological pattern*

| F7 | Planform pattern | | |
|---|---|---|---|
| A | Absence (<5%) of alteration of the natural heterogeneity of geomorphic units and channel width | 0 | |
| B | Alterations for a limited portion of the reach (≤33%) | 3 | |
| C | Consistent alterations for a significant portion of the reach (>33%) | 5 | |

| F8 | Presence of typical fluvial landforms in the floodplain | | |
|---|---|---|---|
| A | Presence of floodplain landforms (oxbow lakes, secondary channels, etc.) | 0 | |
| B | Presence of traces of landforms (abandoned during the last decades) but with possible reactivation | 2 | |
| C | Complete absence of floodplain landforms | 3 | |

*Evaluated only in the case of meandering rivers (now or in the past) excluding groundwater-fed streams*

*Cross-section configuration*

| F9 | Variability of the cross-section | | |
|---|---|---|---|
| A | Absence (≤5%) of alteration of the cross-section natural heterogeneity (channel depth) | 0 | |
| B | Presence of alteration (cross-section homogeneity) for a limited portion of the reach (≤33%) | 3 | |
| C | Presence of alteration (cross-section homogeneity) for a significant portion of the reach (>33%) | 5 | |

*Not evaluated in the case of low energy straight, sinuous, meandering or anabranching channels with natural absence of bars (lowland rivers, low gradients and/or low bedload) and groundwater-fed streams (natural cross-section homogeneity)*

*Bed structure and substrate*

| F10 | Structure of the channel bed | | |
|---|---|---|---|
| A | Natural heterogeneity of bed sediments and no significant armouring and/or clogging | 0 | |
| B | Evident armouring or clogging for ≤50% of the reach | 2 | |
| C1 | Evident armouring or clogging for >50% of the reach or occasional substrate outcrops (≤33% of the reach) related to recent bed-incision of the alluvial substrate | 5 | |
| C2 | Widespread alteration of substrate due to bed revetment or substrate outcrops (>33% of the reach) | 6 | |

*Not evaluated for sand-bed rivers, and for deep rivers when it is not possible to observe the channel bed*

| F11 | Presence of in-channel large wood | | |
|---|---|---|---|
| A | Significant presence of large wood along the whole reach (or "wood transport" reach) | 0 | |
| B | Negligible presence of large wood for ≤50% of the reach | 2 | |
| C | Negligible presence of large wood for >50% of the reach | 3 | |

*Not evaluated above the tree-line and in streams with natural absence of riparian vegetation (e.g. north-European tundra)*

# *Morphological Quality Index (MQI)*

**Vegetation in the fluvial corridor**

| | | | |
|---|---|---|---|
| **F12** | **Width of functional vegetation** | | |
| A | High width of functional vegetation | 0 | |
| B | Medium width of functional vegetation | 2 | |
| C | Low width of functional vegetation | 3 | |

*Not evaluated above the tree-line and in streams with natural absence of riparian vegetation (e.g. north-European tundra)*

| | | | |
|---|---|---|---|
| **F13** | **Linear extension of functional vegetation and presence of emergent aquatic macrophytes** | | |
| A | Riparian vegetation >90% of maximum length, or riparian vegetation>33% and significant presence of emergent aquatic vegetation (low-energy channels) | 0 | |
| B | Riparian vegetation 33÷90%, or riparian vegetation >90% but very limited presence of aquatic vegetation, or riparian vegetation ≤33% but significant presence of aquatic vegetation | 3 | |
| C | Riparian vegetation ≤33%, or <90% but very limited presence of aquatic vegetation | 5 | |

*Riparian vegetation not evaluated above the tree-line and in streams with natural absence (e.g. north-European tundra)*
*Aquatic vegetation evaluated only in low-energy straight, sinuous, meandering or anabranching channels*

## ARTIFICIALITY

**Upstream alteration of longitudinal continuity**

| | | *part.* | *prog.* | *conf.* |
|---|---|---|---|---|
| **A1** | **Upstream alteration of flows** | | | |
| A | No significant alteration (≤10%) of channel-forming discharges and with return interval>10 years | 0 | | |
| B | Significant alteration (>10%) of discharges with return interval>10 years or release of increased low flows downstream dams during dry seasons | 3 | | |
| C | Significant alteration (>10%) of channel-forming discharges | 6 | | |

| | | | |
|---|---|---|---|
| **A2** | **Upstream alteration of sediment discharges** | | |
| 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 | |
| B1 | Dams (area 5-33%) and/or check dams/weirs with total bedload interception (area 33-66%) and/or check dams/weirs with partial or no interception (area>66%) | 3 | |
| B2 | Dams (area 33-66%) and/or check dams/weirs with total bedload interception (area>66%) | 6 | |
| C1 | Dams for drainage area >66% | 9 | |
| C2 | Dam at the upstream boundary of the reach | 12 | |

**Alteration of longitudinal continuity in the reach**

| | | | |
|---|---|---|---|
| **A3** | **Alteration of flows in the reach** | | |
| A | No significant alteration (≤10%) of channel-forming discharges and with return interval>10 years | 0 | |
| B | Significant alteration (>10%) of discharges with return interval>10 years | 3 | |
| C | Significant alteration (>10%) of channel-forming discharges | 6 | |

| | | | |
|---|---|---|---|
| **A4** | **Alteration of sediment discharge in the reach** | | |
| A | Absence of structures for the interception of sediment fluxes (dams, check dams, abstraction weirs) | 0 | |
| B | *Channels with S≤1%:* consolidation check dams and/or abstraction weirs ≤1 every 1000 m<br>*Steep channels (S>1%):* consolidation check dams ≤1 every 200 m and/or open check dams | 4 | |
| C | *Channels with S≤1%:* consolidation check dams and/or abstraction weirs >1 every 1000 m<br>*Steep channels (S>1%):* consolidation check dams >1 every 200 m and/or retention check dams or presence of a dam or artificial reservoir at the downstream boundary (*any bed slope*) | 6 | |
| | *In case of density of interception structures, including bed sills and ramps (see A9), is >1 every d1, add* | 6 | |
| | *In case of density of interception structures, including bed sills and ramps (see A9), is >1 every d2, add* | 12 | |

*where d1=150 m and d2=100 m in steep channels, or d1=750 m and d2=500 m in channels with S≤1%*

# Morphological Quality Index (MQI)

| A5 | Crossing structures | | |
|---|---|---|---|
| A | Absence of crossing structures (bridges, fords, culverts) | 0 | |
| B | Presence of some crossing structure (≤1 every 1000 m in average in the reach) | 2 | |
| C | Presence of many crossing structure (>1 every 1000 m in average in the reach) | 3 | |

## Alteration of lateral continuity

| A6 | Bank protections | | |
|---|---|---|---|
| A | Absence or localized presence of bank protections (≤5% total length of the banks) | 0 | |
| B | Presence of protections for ≤33% total length of the banks (sum of both banks) | 3 | |
| C | Presence of protections for >33% total length of the banks (sum of both banks) | 6 | |

*In case of high density of bank protection (>50%) add* 6

*In case of extremely high density of bank protection (>80%) add* 12

| A7 | Artificial levées | | |
|---|---|---|---|
| A | Absent or set-back levées, or presence of close and/or bank-edge levées ≤10% bank length | 0 | |
| B | Bank-edge levées ≤50%, or ≤33% in case of total of close and/or bank edge>90% | 3 | |
| C | Bank-edge levées >50%, or >33% in case of total of close and/or bank edge>90% | 6 | |

*In case of high density of bank-edge levées (>66%) add* 6

*In case of extremely high density of bank-edge levées (>80%) add* 12

## Alteration of channel morphology and/or substrate

| A8 | Artificial changes of river course | | |
|---|---|---|---|
| A | Absence of artificial changes of river course in the past (meanders cut-off, channel diversions, etc.) | 0 | |
| B | Presence of changes of river course for ≤10% of the reach length | 2 | |
| C | Presence of changes of river course for >10% of the reach length | 3 | |

| A9 | Other bed stabilization structures | | |
|---|---|---|---|
| A | Absence of structures (bed sills/ramps) and revetments absent or localised (≤5%) | 0 | |
| B | Sills or ramps (≤1 every *d*) and/or revetments ≤25% permeable and/or ≤15% impermeable | 3 | |
| C1 | Sills or ramps (>1 every *d*) and/or revetments ≤50% permeable and/or ≤33% impermeable | 6 | |
| C2 | Revetments >50% permeable and/or >33% impermeable | 8 | |

*d=200 m in steep channels (S>1%); d= 1000 m in channels with S≤1%*

*In case of high density of bed revetment (impermeable >50% or permeable >80%) add* 6

*In case of extremely high density of bed revetment (impermeable >80%) add* 12

## Intervention of maintenance and removal

| A10 | Sediment removal | | |
|---|---|---|---|
| A | Absence of recent (last 20 years) and past (last 100 years) significant sediment removal activities | 0 | |
| B1 | Sediment removal activity in the past (last 100 years) but absent during last 20 years | 3 | |
| B2 | Recent sediment removal activity (last 20 years) but absent in the past (last 100 years) | 4 | |
| C | Sediment removal activity either in the past (last 100 years) and during last 20 years | 6 | |

| A11 | Wood removal | | |
|---|---|---|---|
| A | Absence of removal of woody material at least during the last 20 years | 0 | |
| B | Partial removal of woody material during the last 20 years | 2 | |
| C | Total removal of woody material during the last 20 years | 5 | |

*Not evaluated above the tree-line and in streams with natural absence of riparian vegetation (e.g. north-European tundra)*

# *Morphological Quality Index (MQI)*

| **A12** | **Vegetation management** | | |
|---|---|---|---|
| A | No cutting interventions on riparian (last 20 years) and aquatic vegetation (last 5 years) | 0 | |
| B | Selective cuts and/or clear cuts of riparian vegetation ≤50% of the reach and partial or no cutting of aquatic vegetation, or no cutting of riparian but partial or total cutting of aquatic vegetation | 2 | |
| C | Clear cuts of riparian vegetation >50% of the reach, or selective cuts and/or clear cuts of riparian vegetation ≤50% of the reach but total cutting of aquatic vegetation | 5 | |

*Riparian vegetation not evaluated above the tree-line and in streams with natural absence (e.g. north-European tundra)*
*Aquatic vegetation evaluated only in low-energy straight, sinuous, meandering or anabranching channels*

## CHANNEL ADJUSTMENTS

| **CA1** | **Adjustments in channel pattern** | *part.* | *prog.* | *conf.* |
|---|---|---|---|---|
| A | Absence of changes of channel pattern from 1930s - 1960s | 0 | | |
| B | Change to a similar channel pattern from 1930s - 1960s | 3 | | |
| C | Change to a different channel pattern from 1930s - 1960s | 6 | | |

*Not evaluated in the case of small streams where resolution of aerial photos is insufficient*

| **CA2** | **Adjustments in channel width** | | |
|---|---|---|---|
| A | Absent or limited changes (≤15%) from 1930s - 1960s | 0 | |
| B | Moderate changes (15÷35%) from 1930s - 1960s | 3 | |
| C | Intense changes (>35%) from 1930s - 1960s | 6 | |

*Not evaluated in the case of small streams where resolution of aerial photos is insufficient*

| **CA3** | **Bed-level adjustments** | | |
|---|---|---|---|
| A | Negligible bed-level changes (≤0.5 m) | 0 | |
| B | Limited to moderate bed-level changes (0.5÷3 m) | 4 | |
| C1 | Intense bed-level changes (>3 m) | 8 | |
| C2 | Very intense bed-level changes (>6 m) | 12 | |

*Not evaluated in the case of absolute lack of data, information and field evidence*

**Total deviation:** ***Stot =***

**Maximum deviation:** ***Smax* = 142 - *Sna*=**

*where Sna = sum of maximum scores for indicators that have not been applied*

**Morphological Alteration Index:** ***MAI = Stot / Smax =***

*if Stot>Smax, MAI is assumed =1*

**Morphological Quality Index:** ***MQI=1-MAI =***

**Quality class of the reach**

0≤*MQI*<0.3: Very Poor or Bad; 0.3≤*MQI*<0.5: Poor; 0.5≤*MQI*<0.7: Moderate;
0.7≤*MQI<0.85*: Good; 0.85≤*MQI*≤1.0: Very Good or High

# Appendix 3: Guide to the Compilation of the Evaluation Forms

## *Introduction*

This Guide is aimed to provide detailed instructions and support for the compilation of the *MQI* evaluation forms. For each indicator, an extended version of the possible answers is reported. Furthermore, the following information is reported:

- Spatial scale (longitudinal and lateral);
- Type of measurements (e.g. field survey, remote sensing, or other sources of information);
- Typology (confined, partly confined or unconfined);
- Range of application (for those indicators that are not applied in specific cases).

Concerning the longitudinal **spatial scale**, the following general indications are provided. In case of indicators assessed by remote sensing, the longitudinal spatial scale corresponds to the entire reach. In case of indicators which need field survey observation/measurement, the assessment is focussed on the *'site'* scale (i.e., one or preferably more sub-reaches selected as the most representatives of the reach), although additional checks along other sites should be considered (e.g. for indicators which need the definition of the lateral extent and/or continuity along the reach). Finally, artificial elements must be recognised and assessed along the whole reach.

## *Generality and delineation of spatial units*

The first part of the evaluation form is dedicated to some general information, including the **date** of the field survey (although the complete compilation of the evaluation form requires a preparation phase and a conclusion phase of the measurements after the field visit), and the name(s) of the **operators**. Then the name of the **catchment** and of the **stream/river** is indicated. The **upstream and downstream limits** of the reach must be clearly defined (e.g. name of a tributary, if this represents a limit, or planimetric coordinates). It follows the identification code of the **segment** and **reach**, and the reach **length**. In the case of anabranching channels, the reach length is calculated as the average of the single channels. In those indicators which refer to the percentage of reach length, this is intended as the percentage of the total length (i.e. sum of all single channels).

The following part is dedicated to all information and measurements made during the four steps of the general setting and initial segmentation. During *step 1*, the **physiographic setting** (physiographic context and landscape unit) is specified. During *step 2*, the details for the classification of **confinement** are provided. Note that, as for all the indices reported in this section, the operator can report the precise value of the index, or only specify the class (e.g. > 90%, 10÷90% or < 10% for the confinement degree). *Step 3* is dedicated to **channel morphology**. First of all, the name of the image (aerial photo or satellite image) used as a reference for all observations aimed at morphological classification is indicated. Then, all the indices and other information are reported, including the mean bed slope and the mean channel width along the reach. In the case of anabranching rivers, the mean bed slope is calculated as the average of the bed slopes of the single threads, whereas the channel width is calculated as the sum of the widths of all threads. In *step 4*, information regarding **other elements for reach delineation** is reported. Finally, it is possible to report additional available data or information which are useful for the assessment (e.g. sediment sizes and discharges).

## *Geomorphological Functionality*

### Continuity

### *F1:* Longitudinal continuity in sediment and wood flux

**Definition**

This indicator evaluates whether the longitudinal continuity of sediment and wood material is altered by human structures that intercept or create obstacles to their flow (discontinuities due to natural factors, such as rock outcroppings, lakes or landslide dams are not considered).

| Spatial scale | |
|---|---|
| *Longitudinal*: Site/Reach | *Lateral*: Channel |
| **Measurements**: Remote sensing and field survey | |

The assessment does not depend on the number of alterations, but on their relevance: just one structure can cause a complete alteration of the flux, or differently, many structures may have no significant effects (the number of structures is accounted for in the indicators of Artificiality). The main artificial structures are dams, check dams, and weirs. Other alterations can be due to crossing structures (bridges, fords) or also groynes. In the case of a **structure located at the upstream reach limit, this is conventionally assigned to the upstream reach** (see indicators of Artificiality)**, but the effects on the longitudinal continuity are considered for the downstream reach**. Therefore, the effect of a structure located at the downstream limit is not evaluated for that reach, but for the one downstream.

The assessment is first based on remote sensing, noting whether existing structures create a clear differentiation in the presence and extension of depositional forms upstream and downstream from the structure. Field checks are then required to better assess the impact of existing structures (e.g. to verify whether the structure causes a selective flux of sediment and wood).

**EXTENDED ANSWERS**

| Typology | All typologies |
|---|---|
| A | Absence or very negligible presence of alterations in the continuity of sediment and wood flux, that is, there are no significant obstacles or interceptions to the free passage of solid material related to transversal and/or crossing structures (e.g. bridge with no piers or wide span, check dams or weirs completely filled and significant changes in depositional features and sediment size upstream and downstream the structure). In the case of anabranching channels: absence or very negligible presence of alteration in all the anabranches, or slight alteration in a secondary anabranch. |
| B | Slight alteration in the continuity of sediment and wood flux, that is, most solid material is able to flow along the reach. Depositional forms may exist, indicating sedimentation of the coarsest fractions of bedload by crossing structures and/or groynes, but with no complete interception (e.g. bridges with narrow spans and piers, series of consolidation check dams in mountain areas, or check dams filled with coarse sediments but with significant difference in grain size from upstream to downstream); larger sizes of wood is held by bridge piers and/or open check dams. In the case of anabranching channels: slight alteration in the main anabranch or in more anabranches (class |

| | |
|---|---|
| | *B* for the main anabranch or more anabranches), or strong alteration in a secondary anabranch or in more anabranches but absence of alteration in the remaining anabranches (i.e. combination of classes *A* and *C*). |
| C | Strong alteration in the continuity of sediment and wood flux, that is, a strong discontinuity of depositional forms (sediments) exist in upstream and downstream structures because bedload is strongly intercepted (e.g. not filled weirs or check dams or, in mountain systems, check dams filled by fine sediments). In the case of anabranching channels: strong alteration in all the existing anabranches or strong alteration in the main anabranch or in more anabranches and slight alteration in the remaining anabranches (i.e. combination of classes *B* and *C*). |

### *F2:* Presence of a modern floodplain

**DEFINITION**

A river in dynamic equilibrium builds a modern floodplain that is generally inundated for discharges just exceeding channel-forming flows (return interval of 1÷3 years). The presence of a modern, frequently inundated floodplain promotes several important morphological, hydrological and ecological functions (attenuation of flood peak discharges, energy dissipation, fine sediment deposition, groundwater recharge, flood pulse, turnover of riparian habitats, etc.). Channel adjustments (specifically bed incision) or artificial structures (levées) can alter this characteristic form and disconnect the floodplain from channel processes.

Lateral extension and longitudinal continuity of a modern floodplain is considered here as an indicator of existing lateral continuity of water and sediment fluxes.

| **Spatial scale** | |
|---|---|
| *Longitudinal*: Site/Reach | *Lateral*: Entire floodplain (including recent terraces) |
| **Measurements**: Remote sensing and field survey | |

The floodplain is a typical geomorphic feature of **partly confined and unconfined channels**, therefore the indicator is not applied to confined channels (even though, in some cases, small floodplain areas can also be recognized along confined channels). The indicator is not applied in mountain areas along steep alluvial fans (> 3%), where the floodplain is difficult to identify even in natural conditions.

**GEOMORPHOLOGICAL DEFINITION OF MODERN FLOODPLAIN**

A *modern floodplain* (or active or genetic floodplain) is an alluvial, flat surface adjacent to the river, created by lateral and vertical accretion during the present regime conditions. A river in dynamic equilibrium builds a modern floodplain that is generally inundated for discharges just exceeding channel-forming flows (return interval of 1÷3 years).

It is important to note that the **'modern' floodplain** evaluated by this indicator does not correspond to the **entire floodplain**, which is considered to evaluate the confinement, but in general is only a portion of that wider surface. This is clear in recently incised channels (i.e. last 100÷150 years, very common in most European countries), where the modern floodplain corresponds to recent surfaces formed after the last phase of incision. The modern floodplain is therefore distinguished from the **'recent' terraces** (coinciding with abandoned or inactive floodplains), i.e. those surfaces interested by flooding with higher return interval (generally >3 years), and which often correspond to the floodplain before the incision. Accordingly, in case of recent incision (last 100÷150 years) the entire floodplain may include the modern floodplain and the recent terraces.

However, in those cases where incision has been limited (to the order of about 1 m or less), the portions of abandoned channel can be hydrologically identified with a modern floodplain. In such cases, considering the practical difficulty of discriminating them in the field, these surfaces are evaluated as a modern floodplain in *F2.*

The **field identification of a modern floodplain** is based on a series of field evidence: (1) morphological and topographical continuity amongst channel depositional features (i.e. bars); (2) presence of fine sediment; (3) relatively dense vegetation cover, with strong presence of mature vegetation (i.e. trees); (4) evidence of flooding (e.g. woody debris). In some cases field evidence is poorly or non-recognizable (e.g. farming fields, vegetated terraces).

**METHODS FOR FLOODPLAIN DELINEATION AND FOR MEASURING CONTINUITY AND LATERAL EXTENT**

The identification and delineation of the modern floodplain is carried out by remote sensing and field survey. In some cases, additional methods can be used, including: (a) photo interpretation and/or DEMs, provided they are at a resolution sufficient for identifying differences in elevation between alluvial surfaces; (b) hydraulic modelling: the results of modelling normally used for the delimitation of flooding areas can support the delineation of the floodplain (i.e. for floods of low return period).

The evaluation of this indicator is based on the assessment of the modern floodplain **continuity**, defined as the percentage of reach length with presence of modern floodplain, even only on one side, and **lateral extent,** i.e. its overall width (sum of both sides). Islands are included in the calculation of both modern floodplain continuity and lateral extent, except in the case of terraced islands (i.e. islands higher than the level of modern floodplain). For anabranching channels, the continuity is assessed for all single threads, and is calculated as a percentage of the sum of the length of all threads). Class *A* is associated to a lateral extent at least equal to $nW$, where $W$ is the channel width, $n = 2$ for single-thread or anabranching channels, and $n = 1$ for braided or wandering channels. The lower value of $n$ for braided and wandering channels is explained by the narrower channel area involved in lateral mobility and the relatively higher channel width compared to single-thread channels. In the case of partly-confined channels, where the modern floodplain occupies all the available valley floor, the reach is in class A even if the lateral extent is lower than $nW$.

Measures of lateral extent from remote sensing (GIS) can be carried out in two modalities: (1) in terms of an average along the reach of values measured on representative transects; (2) by calculating the ratio "floodplain area/channel area". In some particular cases (i.e. problems in the delimitation of the modern floodplain area from remote sensing) the mean modern floodplain width can be measured in the field in representative sections.

**INTERACTION WITH OTHER INDICATORS**

*F2* interacts with several others indicators, mainly the following:
(1) Vegetation in the fluvial corridor (*F12* and *F13*): in some cases, the vegetated fluvial corridor adjacent to the river channel corresponds or includes the modern floodplain. In fact, the vegetated surfaces are often at a lower level compared to agricultural lands. In other cases these vegetated areas correspond to terraces. For these reasons, the identification of the modern floodplain and its distinction from the vegetated fluvial corridor should be carried out in the field. On the other hand, agricultural lands are generally terraces, except in the case where there is no bed incision.
(2) The presence of artificial levées (*A7*) automatically excludes that the surfaces external to the levées may be modern floodplain, while the surface included between set-back levées and the bank edges can potentially be a modern floodplain or a terrace.
(3) Adjustments in channel width (*CA2*): previous portions of channel bed abandoned by narrowing, associated with limited or moderate bed incision, are likely to correspond to a modern floodplain.

(4) Vertical adjustments (*CA3*): incision causes the hydrological disconnection between the river channel and its floodplain. However, a new floodplain surface could be developed after bed incision, therefore vegetated surfaces adjacent to the stream could be a modern floodplain. On the other hand, if no incision has occurred, the modern floodplain often corresponds to the entire floodplain (even if it is completely occupied by farming fields).

**FLOW-CHART TO GUIDE THE DEFINITION OF THE CLASS**

The figure below shows a diagram to support the identification of the modern floodplain taking into account the interaction of *F2* with the other related indicators (mainly *CA3*). The diagram assumes that artificial levées are absent or, if present, the modern floodplain cannot extend behind them. The proposed scheme is not exhaustive, given that other particular cases not included here could occur.

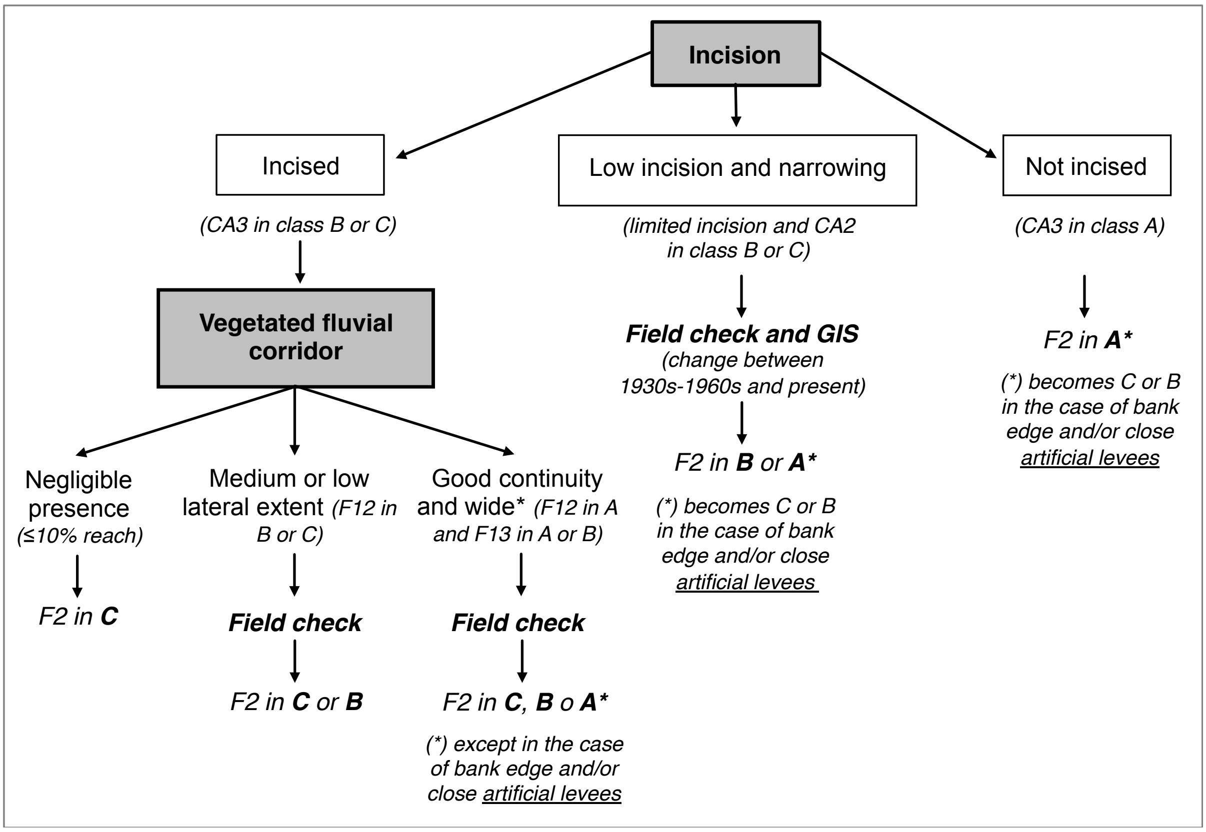



**Figure 1 Sketch of the interactions between *F2* and other related indicators. Class B may correspond to B1 or B2, depending on the width of the modern floodplain.**

**EXTENDED ANSWERS**

| | |
|---|---|
| Typology | Partly confined or unconfined |
| Range of application | Not evaluated in the case of mountain streams along steep (>3%) alluvial fans |
| A | Presence of a relatively continuous (> 66% of the reach length) and sufficiently wide modern floodplain, that is, when the mean width (sum on the two sides) is at least twice the channel width (*W*) in the case of single-thread or anabranching channels, or at least 1 *W* in the case of braided or wandering channels. For anabranching channels, the reach length is the sum of the lengths of the individual anabranches. |
| B1 | Presence of a discontinuous modern floodplain (10÷66% of the reach length) but sufficiently wide, that is, when the mean width (sum on the two sides) is at least twice the channel width (*W*) in the case of single-thread or anabranching channels, or at least 1 *W* in the case of braided or wandering channels.<br>Or presence of a continuous (> 66% of the reach length) but not sufficiently wide modern floodplain, that is, when the mean width (sum on the two sides) is ≤ 2 *W* in the case of single-thread or anabranching channels, or ≤ 1 *W* in the case of braided or wandering channels. |
| B2 | Presence of a discontinuous modern floodplain (10÷66% of the reach length) not sufficiently wide, that is, when the mean width (sum on the two sides) is ≤ 2 *W* in the case of single-thread or anabranching channels, or ≤ 1 *W* in the case of braided or wandering channels. |
| C | Absence of a modern floodplain or negligible presence (≤ 10% of the reach length of any width). |

## *F3:* Hillslope – river corridor connectivity

**Description**

The linkage between hillslopes and river corridor is evaluated here in the case of **confined channels**, as this is very important for the natural supply of sediment and large wood. The indicator refers to the overall river corridor (including small and discontinuous portions of modern floodplain and/or recent terraces which can eventually be present along confined streams), given that a large quantity of hillslope material can temporarily be stored along small portions of modern floodplains or terraces before being involved in sediment transport. On the other hand, the indicator does not evaluate the presence of a potentially erodible corridor.

The connectivity between hillslopes and river corridor is based on the presence and percentage on the reach length (i.e. sum of both sides) of elements of disconnection (e.g. roads, as well as structures for landslides protection) in a **strip conventionally 50 m wide for each river side**. The strip can easily be obtained from remote sensing, once the river corridor is defined, but a field survey to check the presence of intercepting structures is also recommended (e.g. in forested river corridors). The width of 50 m, for simplicity, is evaluated as the horizontal projection, although it is evident that areas with variable gradient may eventually have a slope (that is the most significant part) narrower than 50 m. This is, for example, the case of streams confined by alluvial fans or terraces, where the slope is narrower than 50 m, while sub-horizontal surfaces are located on the top of the hillslope. In such a case, the sub-horizontal surfaces are excluded from the analysis.

| Spatial scale | |
|---|---|
| *Longitudinal*: Reach | *Lateral*: Floodplain/adjacent hillslopes |
| **Measurements**: Remote sensing and field survey | |

**EXTENDED ANSWERS**

| Typology | Confined |
|---|---|
| A | A full connectivity exists between hillslopes and river corridor (channel and floodplain), extending for most of the reach (> 90%). |
| B | The connectivity between hillslopes and river corridor exists for a significant portion of the reach (33÷90%). |
| C | The connectivity between hillslopes and river corridor exists for a small portion of the reach (≤ 33%). |

## *F4:* Processes of bank retreat

**DESCRIPTION**

Bank erosion is a key process contributing to sediment supply and recovery, as well as to the development of the floodplain and the turnover of riparian vegetation and habitats. It is necessary to evaluate whether bank erosion processes occur as expected for a given river typology (e.g. erosion along the outer meander bend in meandering channels), or if there is a significant difference, such as absence due to widespread bank control, or excessive bank failures due to instability of the system (e.g. due to channel incision).

| Spatial scale | |
|---|---|
| *Longitudinal*: Site/Reach | *Lateral*: Channel |
| **Measurements**: Remote sensing and field survey | |

This indicator is applied only to **partly confined and unconfined channels**, given that in confined channels the banks are often directly in contact with the slopes, and hillslope processes dominate (see indicator *F3*). Moreover this indicator is **not applied in low energy rivers** (i.e. low slope and/or low bedload), such as lowland plain and coastal plain rivers, low-energy anabranching (i.e. anastomosing) rivers, where processes of bank retreat are naturally absent or very infrequent, and alluvial **groundwater-fed streams.** The latter is the case of rivers fed by groundwater springs or by karst springs, i.e. largely maintained by contributions from groundwater during low flow periods (see for example Berg and Allen, 2007), which are quite common, among other areas, along the southern side of the Alps and the Po Plain in northern Italy (Fontana et al., 2014).

The indicator evaluates whether bank erosion processes are altered along the reach. Two opposite situations of alteration are considered: (1) bank erosion processes are lacking or they clearly occur less frequently than expected; (2) bank erosion processes are clearly in excess compared to unaltered conditions. The two situations are investigated as follows.

(1) Bank erosion processes occur **less frequently** than expected. The scarce occurrence of bank erosion may not only be related to **bank protections**, but also to other interventions that may induce a significant **reduction in bed slope** and therefore in stream energy (e.g., upstream of dams, weirs, check dams, etc.). Three classes are defined: (A) frequent retreating banks; (B) retreating banks less frequent than expected, i.e. bank erosion is observed locally and for limited lengths; (C) complete absence of

negligible presence (very localized erosion) of retreating banks. The definition of precise values of expected bank erosion in natural conditions is extremely problematic. However, indicative minimum levels of expected bank erosion are provided to define the thresholds of the different classes (see extended answers) in order to reduce subjectivity in the choice. Furthermore, in unaltered conditions (class A) a sufficiently homogeneous distribution of retreating banks along the reach is expected, i.e. the minimum level of expected bank erosion should not be concentrated only in a small portion of the reach (see extended answers).
(2) An **excessive** amount of bank erosion occurs along the reach. In this case, the indicator intends to account for those situations of widespread bank failures related to bed **incision** or to strong alterations of the flow regime: for example, **hydropeaking** may cause rapid water level oscillations inducing an excessive level of mass failures along the reach. In the first case, two diagnostic elements can be used to assess this condition: (1) in most retreating banks, mass failures are the dominant processes responsible for bank retreat (e.g., rotational, planar, cantilever failures, etc.); (2) this strong alteration is normally associated to intense bed-level changes (i.e. the indicator *CA3* is in class C) and bank failures occurring along scarps delimiting low terraces generated by this incision. In the case of hydropeaking, the excessive erosion may not necessarily occur in reaches affected by intense incision, but this situation is recognised when the occurrence of hydropeaking along the reach is evident, and bank retreat mainly occurs due to mass failures, because of the rapid drawdown during the recessional phase of the hydrograph.

The length of eroding banks along the reach is evaluated from **remote sensing**, while **field survey** is useful for interpreting the types of bank erosion processes, i.e. mass failures in the case of excessive erosion by incision or hydropeaking, or for verifying situations which are not sufficiently clear from remote sensing. Therefore, the frequency of bank erosions is referred to the date of the remote sensing image used for the overall application of the index, and does not require updating in the field in case of some new bank erosion being noted. Sub-reaches where the channel is directly in contact with hillslopes or ancient terraces are excluded from the assessment.

**EXTENDED ANSWERS**

| | |
|---|---|
| **Typology** | Partly confined or unconfined |
| **Range of application** | Not evaluated in the case of straight, sinuous and low-energy anabranching (anastomosing) channels with low energy (lowland plain, low bed-slope and/or bedload), and groudwater-fed streams |
| **A** | Bank erosion occurs for a sufficient length (a minimum of >10% of the total length of the banks, excluding portions directly in contact with hillslopes or ancient terraces), and with a sufficiently homogeneous distribution (i.e. bank erosions are distributed along >33% of the reach length), as expected for the river typology. For instance, erosion frequently occurs in the outer bank of bends (single-thread sinuous – meandering channels) and/or in front of bars (braided or wandering channels). |
| **B** | Moderate alteration of bank erosion processes: bank erosion occurs less frequently than expected for the river typology (≤10% of the total length of the banks), because impeded by protective elements and/or scarce channel dynamics related to other human interventions (e.g., reduction in bed slope related to check dams or weirs). Or bank erosion occurring for >10% but concentrated on a limited portion of the reach (≤33% of reach length).<br>Or significant presence (>25% of the total length of the banks) of unstable, eroding banks by |

| | |
|---|---|
| | mass failure related to excessive bank height because of bed incision or to alterations of flow regime (hydropeaking). |
| C | Complete absence (very localized erosion, i.e. ≤2% of the total length of the banks) of retreating riverbanks due to excessive human control (bank protection, reduction in bed slope related to check dams or weirs) (except for reaches at low energy: see range of application).<br>Or significant presence (>50% of the total length of the banks) of unstable, eroding banks by mass failure related to excessive bank height because of bed incision or to alterations of flow regime (hydropeaking). |

## *F5:* Presence of a potentially erodible corridor

**DEFINITION**

The presence of a potentially erodible corridor is nowadays widely recognised as a positive attribute of rivers. This indicator evaluates the possibility of the river to move laterally over the next decades (as opposed to the indicator *F4* which evaluates the current processes of bank erosion). As for *F4*, this is applied to **partly confined and unconfined** rivers. The presence of fixing structures or artificial elements that would be protected against possible erosion may alter the expected natural lateral mobility of these rivers.

| Spatial scale | |
|---|---|
| *Longitudinal*: Reach | *Lateral*: Entire floodplain (including recent terraces) |
| **Measurements**: Remote sensing | |

A rapid assessment is performed by evaluating whether the width and longitudinal continuity of areas without relevant human structures or infrastructures (e.g. houses, roads) are within or out of given ranges. Artificial structures which limit the width of the erodible corridor are: bank protection structures, embankments, artificial levées, as well as all other anthropic elements (e.g. houses, main roads) which would be protected by lateral channel dynamics. Past bank protection structures (e.g. groynes), even if no longer in contact with the channel, are considered as structures which can potentially prevent the lateral channel dynamics (while they are not taken into account in the indicator *A6*). Other minor structures, such as farming fields and dirt patches or roads, are not taken into account by this indicator.

The width of the potentially erodible corridor is defined and measured as for the indicator *F2*. For class *A*, the width of the potentially erodible corridor (the sum of the two sides, but eventually can be extended only on one side) must be at least equal to $nW$, where $W$ is the channel width, $n$ = 2 for single thread or anabranching channels, and $n$ = 1 for braided or wandering channels.

The continuity is measured (similarly to the indicator *F2*) as the percentage of reach length with the presence of a potentially erodible corridor, even only on one side. In the case of **meandering channels**, the continuity of the potentially erodible corridor is calculated exclusively as a % of the length of the external meander banks, i.e. inner meander banks are not evaluated.

In the case of anabranching channels, the continuity of the potentially erodible corridor is calculated as % of the sum of the lengths of all the anabranches, and the width includes islands (if erodible). In the case of partly confined channels, where the potentially erodible corridor corresponds to all the available floodplain, the reach is attributed class *A* even if the width of the erodible corridor is lower than $nW$.

**EXTENDED ANSWERS**

| Typology | Partly confined or unconfined |
|---|---|
| A | Presence of a relatively continuous (> 66% of the reach length) and sufficiently wide potentially erodible corridor (EC), that is, the mean width (sum of the two sides) is at least twice the channel width (*W*) in the case of single-thread or anabranching channels, or at least 1 *W* for braided or wandering channels. In the case of anabranching channels, the reach length is intended as the sum of the lengths of all anabranches. |
| B | Presence of a potentially erodible corridor (EC) with medium continuity (33÷66% of the reach length) and width, that is, the mean width (sum of the two sides) is at least twice the channel width (*W*) in case of single-thread or anabranching channels, or at least 1 *W* for braided or wandering channels; or a potentially EC for > 66% of the reach length but not sufficiently wide. |
| C | Presence of a potentially erodible corridor (EC) of any width but with low continuity (≤ 33% of the reach length). |

## Morphology

### *F6:* Bed configuration – valley slope

**DEFINITION**

Geomorphic units characterizing the channel configuration represent the main focus of the first two indicators of morphology. They are applied either to confined single-thread channels (*F6*) or to unconfined – partly confined and confined transitional or multi-thread channels (*F7*) respectively.

In the case of confined single-thread channels, the planimetric pattern is imposed by the hillslopes and therefore is not significant in terms of morphological assessment, while bed configuration (i.e., the instream geomorphic units characterizing the channel bed) is a diagnostic element of the morphological functionality. This indicator evaluates whether or not the presence of transversal structures has altered the expected bed configuration (cascade, step-pool, plane bed, riffle-pool, dune-ripple) based on the mean bed slope of the reach. In fact, a strong correlation exists between bed slope and configuration, that is, for increasing slopes the following order of forms is expected: dune-ripples (only in sand-bed channels), riffle-pool, plane bed, step-pool / cascade. These morphologies have ecological implications as each of them is characterized by a mosaic of typical habitats.

The existence of a transversal structure can cause an artificial lowering of the local energy slope and therefore a possible alteration of the bed configuration and, consequently, of the associated habitats. This indicator intends therefore to evaluate the magnitude of change caused by transversal structures and not just their presence (which is evaluated in the indicators of artificiality).

| Spatial Scale | |
|---|---|
| *Longitudinal*: Site/Reach | *Lateral*: Channel |
| **Measurements**: Field survey and Remote sensing | |

This indicator is evaluated only in the case of **alluvial single thread confined channels** (in the case of multi-thread or wandering channels, it is substituted by *F7*, therefore *F6* and *F7* are necessarily alternatives).

The operator should determine the mean valley slope along the reach (based on the longitudinal bed profile already used during the segmentation phase), and then define the **expected bed form** according to Table 1. Class limits may have some overlap, due to reach local conditions, which can modify (expand/reduce) the boundaries between bed configuration morphologies. Typical alterations of bed configuration are associated with hydraulic structures on high gradient channels (i.e. check dams on step-pool morphology), which aim to limit river energy and prevent bedload transport. However, the amount of bed configuration alteration depends on the initial reach conditions, the local bedload dynamic and the geometry of the structures (width, number and distance between structures): in some cases, for example, check dams do not modify the bed configuration morphology (from one type to another) but only the size of morphological units (e.g. step, pools, etc.). In low gradient channels (i.e. about less than 0.2%), bed configuration depends on the bed sediment size (gravel or sand) and bank sediment type (cohesive or non-cohesive). This allows to distinguish dune-ripple channels (i.e. sand substrate and deeper) from riffle-pool channels (i.e. gravel substrate and shallower), where single-thread dune-ripple perennial channels cannot develop at a higher bed slope (> 0.2%). Riffle-pool and plane-bed morphologies may also have some overlap in terms of bed slope (between 1 and 2%) as well as plane-bed and step-pool morphologies (between 3 and 4%). This variability depends on the local bedload conditions (amount and transport capacity) and the lateral confinement imposed by hillslopes.

The **mean valley slope** along the reach is simply calculated as the ratio between the overall difference in elevation and the reach length. In the case of long reaches in which the bed slope is highly variable, it is suggested to calculate the bed slope in sub-reaches (eventually delimited by crossing structures). Should the reach limit correspond to a crossing structure (dam or weir), bed elevation immediately downstream from the structure (corresponding to the original bed elevation) is considered for the calculation of the mean slope. In the case of an artificial reservoir being located in the downstream limit of the reach, the lower bed elevation used for valley slope calculation should correspond to the starting point of the reservoir.

**Table 1 Relations between range of bed slope and expected bed forms.**

| Bed forms | Dominant grain size | Range of bed slope |
|---|---|---|
| Dune-ripple | Sand and fine gravel | ≤ 0.2 |
| Riffle-pool | Gravel and cobbles | < 2 |
| Plane bed | Cobbles and gravel | 1÷4 |
| Step-pool/cascade | Boulders and cobbles | > 3 |

The assessment is carried out in the field (if possible by remote sensing) by identifying the prevailing bed configuration morphology and checking its consistency with the expected morphology based on Table 1. When artificial crossing structures are present, bed configuration is evaluated between the structures. In the absence of crossing structures, possible differences between the expected and the observed morphology can be due to local natural factors (e.g. log steps, landsides, moraines, etc.) and are not considered as alteration.

**EXTENDED ANSWERS**

| | |
|---|---|
| **Typology** | Confined |
| **Range of application** | Applied to alluvial single-thread channels. Not evaluated in the case of confined with bedrock or colluvial channels, and in the case of deep streams when it is not possible to observe the bed configuration |
| **A** | Bed forms consistent with the mean valley slope: bed configuration corresponds to that expected, based on the mean valley slope along the reach (Table 1), or bed forms not consistent for a length ≤ 33% of the reach. Included in this class are also the morphologies imposed by natural factors (e.g. log steps, landslides, etc.) which locally can determine unexpected bed forms (e.g. riffles in a steep reach, step-pool in a low gradient reach). |
| **B** | Bed forms not consistent with the mean valley slope for a length > 33% and ≤ 66% of the reach, because bed configuration does not correspond to that expected, based on the mean valley slope along the reach (Table 1), because of presence of transversal structures (dams, check dams, weirs, sills, ramps, etc.). |
| **C** | Bed forms not consistent with the mean valley slope for a length > 66% of the reach, because bed configuration does not correspond to that expected, based on the mean valley slope along the reach (Table 1), because of presence of transversal structures (dams, check dams, weirs, sills, ramps, etc.). |

## *F7:* Planform pattern

**DEFINITION**

This indicator concerns the general features characterizing the planform pattern of alluvial channels, including the geomorphic units and the longitudinal variability in channel width (while the morphological characteristics in cross-section are separately assessed by *F9*). The aim is to evaluate whether these features are those expected for the channel pattern (e.g., braiding, meandering, etc.), or whether there are alterations in their presence and spatial distribution. The presence of instream geomorphic units, as well as the variability of channel width, have important implications in terms of ecological conditions, as they determine the availability and variability of physical habitats. Past changes in channel planform pattern related to human interventions (e.g., meander cutoff) or channel adjustments are not considered by this indicator, as they are evaluated separately in other indicators (*A8*, *CA1*, and *CA2*).

Differently from *F6*, this indicator assesses **geomorphic units** which characterize the planform pattern, while no consideration is made in this case on the bed configuration. The geomorphic units are those typical of alluvial channels, such as bars, islands, benches, as well as secondary channels or anabranches which characterize multi-thread morphological patterns (e.g. braided, anabranching). Altered situations can be related to the presence of artificial elements, including interventions/actions which modify the normal pattern of geomorphic units (e.g. transversal structures, channel resectioning, instream sediment or vegetation removal, etc.) or can be associated to channel adjustments (e.g. incised reaches with the disappearance of geomorphic units). An increase of geomorphic units related to some artificial element can also be an alteration. For example, the occurrence of bars and braiding caused by a local alteration of sediment flow (e.g. upstream and/or downstream a bridge or another transversal structure) along a single-thread channel is evaluated as an alteration.

**Longitudinal variability in channel width** along the reach is considered as an additional feature of the overall planimetric characteristics. For example, braided channels are normally characterized by a succession of nodes-islands, as well as meandering channels with point bars which normally have some variability in channel width, while a lack of width heterogeneity may be caused by artificially fixed banks.

| Spatial scale | |
|---|---|
| *Longitudinal*: Reach | *Lateral*: Channel |
| **Measurements**: Field survey and/or remote sensing | |

The indicator is applied to **partly confined and unconfined channels**, as well as to **wandering or multi-thread confined channels** (for single-thread confined channels, the indicator *F6* is applied). The indicator is mainly evaluated by **remote sensing** integrated with **field survey** at representative sites.

**APPLICATION OF THE INDICATOR TO DIFFERENT CASES**

For the application of this indicator, it is necessary to contextualize the assessment to the type of channel pattern characterizing the reach. Three main situations can be considered in terms of **morphological typologies**: (1) single-thread channels, (2) wandering or braided channels, and (3) anabranching channels.
(1) **Single-thread channels**. Artificial channel fixation and/or excessive channel maintenance (e.g. bar clearing) are the most frequent human interventions altering the planform pattern in single-thread channels (i.e. a lack of typical geomorphic units and of longitudinal variability in channel width).
(2) **Wandering and braided channel**. Classification of the reach as one of these river types during the segmentation phase implies that characteristic geomorphic features (mid-channel bars, bifurcations, etc.) are necessarily present along the reach, but can locally be modified by the presence of artificial structures (e.g. local loss of braiding pattern because of transversal structures).
(3) **Anabranching channels**. Anabranching channels are characterised by the presence of various anabranches separated by vegetated islands. Each anabranch can exhibit a specific morphology attributable to the other channel types described above. In the case of low energy anabranching channels (i.e. anastomosing), the single anabranch channels can be described as straight to meandering single-thread. In the case of high energy anabranching, single anabranches may include bars and exhibit a wandering or even a braided channel morphology. Therefore, for anabranching channels the assessment of channel morphology can be referred to other channel types.

In terms of the **longitudinal distribution of the alteration** along the reach, the following main cases can occur, and it should be considered here whether or not the observed channel pattern is the one expected in the context of its segment and landscape unit setting.
(1) A **portion of the reach** exhibits the natural pattern of geomorphic units characterizing a given morphology, but there are other portions where this morphological planform pattern is altered. In this case the evaluation is straightforward because the unaltered portions are actually considered as the reference pattern of geomorphic units and width variability characterizing the reach morphological type (for example, a reach classified as braided may have some portion where the typical characteristics of the braided pattern are not present).
(2) The **entire reach** exhibits a pattern of geomorphic units and/or width variability which is not expected in the physical context of the river's location. In such cases, some caution is required to correctly evaluate whether or not there is a sufficient evidence to consider the whole reach as altered. A favourable case is when, upstream and downstream from the investigated reach, the planform pattern is characterized by clearly distinct geomorphic units and/or width variability, and a clear human factor for such a

different pattern along the reach is identified. For example, a single-thread reach characterized by fixed banks and heavy maintenance activity (sediment and wood removal) within a segment exhibiting a typical braiding pattern can be considered as entirely altered. Other causes of alteration of the pattern of geomorphic units can be indirectly related to human activities. For example, a deeply incised river (where incision is related to sediment removal or strong interception of bedload upstream) with a loss of the alluvial substrate and associated geomorphic units, in a context where an alluvial channel with abundance of bars is expected, can be considered as an alteration. A more problematic case could be of a single-thread reach with completely fixed banks and absence of geomorphic units and width variability. The absence of width variability due to regularly fixed banks can be considered as a sufficient condition to evaluate the reach as altered. Differently, a low-energy channel (lowland rivers, low gradient and/or low bedload) with erodible banks, width homogeneity and absence of geomorphic units is not considered as altered.

A particular case for the application of this indicator is when some **river restoration intervention** has recently been carried out along the reach. The removal of constrains (e.g., fixed banks) may induce a natural occurrence of geomorphic units (and width variability) which can be considered as a morphological change towards a more natural planform pattern: therefore, in such cases, the indicator changes from more altered to less altered conditions. More problematic is the case of morphological restoration (i.e. artificial modification in channel pattern), for example when a completely new planform pattern is imposed (from a braided to a meandering). In such a case, restoration could be considered as an alteration of the planform pattern. In general, the indicator *F7* should not be applied for the years immediately after the intervention since the river needs a sufficient time to adapt to the newly imposed (restored) conditions. A few years (i.e. at least 5 years) are required following the restoration intervention for correctly interpreting the new condition.

**EXTENDED ANSWERS**

| | |
|---|---|
| **Typology** | All typologies |
| **Range of application** | In the case of confined channels it is applied only to multi-thread or wandering morphologies. It is not applied in the case of recent (last 5 years) interventions of morphological restoration. |
| **A** | Absence or negligible presence (< 5% of the reach length) of alteration of the natural heterogeneity of geomorphic units and channel width expected for that river type.<br>*Braided:* typical presence of a multi-thread configuration with several bifurcations and longitudinal bars, frequent pioneer islands and some mature islands, longitudinal variability of channel width with node-island alternation.<br>*Anabranching:* typical presence of a multi-thread pattern with variable degree of sinuosity and anabranch channels separated by vegetated islands.<br>*Wandering*: typical alternate side bars, chute cut-offs, low-water channel highly sinuous and relatively narrow within the bankfull channel, localized braiding phenomena, presence of pioneer islands and in some cases mature islands, longitudinal variability of channel width.<br>*Sinuous or meandering with bars*: side or point bars, possible chute cut-offs, longitudinal variability of channel width in relation to the presence of bars and curvatures. *Sinuous pseudo-meandering*: typical alternate side bars, chute cut-offs, low-water channel highly sinuous and relatively narrow within the bankfull channel, longitudinal variability of channel width but less |

| | |
|---|---|
| | evident than in wandering – braided channels.<br>*Low energy straight, sinuous, meandering, anabranching (anastomosing)*: they do not necessarily exhibit a significant heterogeneity of geomorphic units and variability of channel width. |
| B | Alteration for a limited portion of the reach (≤ 33% of the reach length) of the natural heterogeneity of geomorphic units and channel width expected for that river type. |
| C | Significant alteration for a significant portion of the reach (> 33% of the reach length) of the natural heterogeneity of geomorphic units and channel width expected for that river type. |

## *F8:* Presence of typical fluvial landforms in the floodplain

**DEFINITION**

This indicator is applied to meandering and low-energy anabranching rivers and accounts for the presence or absence of typical fluvial forms (such as oxbow lakes, secondary channels more or less hydrologically connected to the channel, etc.) that are normally expected to exist in the floodplain. These fluvial forms have an important geomorphological and hydraulic role, as well as an ecological relevance in determining floodplain habitats. The absence of these fluvial forms indicates a certain degree of alteration of the morphological functionality of the river. Note that the floodplain evaluated in this indicator is the entire floodplain (modern floodplain and possible recent terraces).

| Spatial scale | |
|---|---|
| *Longitudinal*: Reach | *Lateral*: Entire floodplain (including recent terraces) |
| **Measurements**: Remote sensing | |

The indicator is applied only to **meandering and low-energy anabranching (i.e. anastomosing) rivers,** even in the case of the river having a meandering pattern in the past which then disappeared due to human interventions (e.g. channelization, artificial cut-off). It is not applied to channels which never developed a meandering pattern (i.e. braided, wandering and all confined channels). **Groundwater-fed streams** are excluded (also if they are meandering), because an absence of fluvial forms in the floodplain may be related to their low dynamics. The assessment is carried out by **remote sensing**.

Class *A* is assigned to reaches with existing typical fluvial forms of floodplain which developed during the current hydrological regime conditions, i.e. in the case where these are hydrologically connected with the channel. Class *B* is assigned to reaches where the fluvial forms in the floodplain are not contemporary but can potentially be reconnected by restoration measures (e.g. excavation of secondary channels), or by natural morphological recovery (e.g. channel aggradation). To evaluate the potentiality of reactivation of these fluvial forms, consistently with the indicators of channel adjustment (*CA1* and *CA2*), aerial photos of 1930s-1960s period can be used to verify whether these forms were active during that time and then disconnected by bed incision.

Abandoned portions of the channel related to narrowing are not accounted for in this indicator (indicator *CA2* is used for this process). The indicator does not evaluate the frequency or the areal extent of fluvial forms, but only their presence/absence in the floodplain.

**EXTENDED ANSWERS**

| | | |
|---|---|---|
| Typology | | Partly confined or unconfined |
| Range of application | | It is applied only to meandering and low-energy anabranching (i.e. anastomosing) channels (now or in the past), excluding groundwater-fed streams |
| A | Presence of natural fluvial forms in the floodplain related to the meandering and anastomosing channel dynamics (oxbow lakes, secondary channels, traces of abandoned meanders, wet zones, etc.). | |
| B | Presence of traces of fluvial forms in the floodplain (abandoned during the last decades), now not in connection with the present channel but with possible reactivation by interventions or recovery processes. | |
| C | Complete absence of fluvial forms in the floodplain related to the meandering and anastomosing channel dynamics. | |

## *F9:* Variability of the cross-section

**DEFINITION**

This indicator evaluates channel variability in cross-section, in terms of channel depth, expected for the channel morphology of the reach as a consequence of the presence and heterogeneity of geomorphic units. The morphological heterogeneity of cross-sections is highly relevant for habitat diversity in many river systems. In fact, homogenous cross-sections are usually associated to altered conditions (except in the case of low energy reaches, which can naturally present a low diversity of forms). Such alterations can be related to the presence of artificial elements (e.g. bank protections), channel maintenance interventions (e.g. occasional or periodic channel resectioning), or to human related channel adjustments (e.g. incision due to sediment starvation).

| Spatial scale | |
|---|---|
| *Longitudinal*: Site/Reach | *Lateral*: Channel |
| **Measurements**: Field survey and remote sensing | |

The indicator is applied to all types of confinement typologies.

In the case of **confined channels**, the assessment of the indicator focuses on the cross-sectional variability of water depth and velocity, mainly examining the channel bed and then secondarily its banks where, in most cases, the presence of zones of flow separation should be expected. The indicator is applied in the **field** along one or more representative sites.

In **partly confined** and **unconfined channels**, the indicator is not evaluated in the case of low-energy straight, sinuous, meandering or anabranching (i.e. anastomosing) channels, or in the case of **groundwater-fed streams**, with natural absence of bars and where the cross-section can be naturally quite homogeneous (lowland, low gradient and/or low bedload channels). Conversely, in low-energy channels crossing plains modelled by **fluvio-glacial processes** (e.g., in North Europe), heterogeneity can be observed of the cross-section as a consequence of the natural **variability of bank and bed sediments** (e.g., from fine material to boulders): in such a case the indicator is evaluated.

The indicator is applied from **remote sensing** (width variability along the reach) and in the **field** (cross-sectional depth variability) along one or more representative sites.

The presence of **pioneer islands**, mainly along partly confined and unconfined channels, is an important element which contributes considerably to the cross-section heterogeneity. In the case of **braided channels**, the depth variability in cross-section is naturally high (because of the multi-channel pattern), except in the case of interventions (e.g. resectioning, sediment or vegetation removal) which may maintain the overall braiding pattern but alter the heterogeneity in cross-section.

The presence of **bank protections** is not sufficient for evaluating the channel as altered in terms of cross-sectional variability. In fact, these structures over time can become morphologically masked by vegetation and sediments, and therefore be characterised by near-natural cross-section variability. The presence of these structures is nonetheless evaluated through the indicators of artificiality. If channel banks are strongly geometrical (e.g. near vertical concrete walls, regular ripraps), the relative channel length occupied by bank protections is considered as altered only in the case of streams featuring a width-to-depth ratio <10, i.e. where the banks represent a relevant portion of the bankfull wetted channel. In other terms, in wide channels – relative to their depth – the presence of artificially regular banks alone is not sufficient for considering cross-section variability as altered.

In the case where **alterations** are **located asymmetrically**, i.e. only on one side of the river channel (e.g. presence of bank protection structures only on one bank in a relatively narrow stream), the altered reach length is counted as a percentage of the altered banks over the total bank length (sum of both banks) (e.g. an alteration along one bank for a length of 100 m corresponds to an altered reach length of 50 m).

**EXTENDED ANSWERS**

| Typology | Confined |
|---|---|
| A | Absence or localized presence (≤ 5% of the reach length) of alterations of the natural cross-sectional variability along the entire reach: a natural variability of the cross section (channel depth/velocity) exists – in relation to the presence of bedforms, bars, vegetation, boulders, influence of hillslopes. |
| B | Presence of alterations of the natural cross-sectional variability (channel depth/velocity) for a limited portion of the reach (≤ 33% of the reach length). |
| C | Presence of alterations of the natural cross-sectional variability (channel depth/velocity) for a significant portion of the reach (> 33% of the reach length). |

| Typology | Partly confined or unconfined |
|---|---|
| Range of application | Not evaluated in the case of low-energy straight, sinuous, meandering or anabranching (anastomosing) channels with natural absence of bars (lowland rivers, low gradients and/or low bedload) and in the case of groundwater-fed streams (natural cross-section homogeneity) |
| A | Absence or localized presence (≤ 5% of the reach length) of alteration of the natural cross-sectional variability (channel depth) along the reach: a natural altimetric variability in cross-section exists, in relation to the presence of geomorphic units (side or point bars, pioneer or mature islands, secondary channels, and natural banks). |
| B | Presence of alteration of the natural cross-sectional variability (channel depth) for a limited portion of the reach (≤ 33% of the reach length). |
| C | Presence of alteration of the natural cross-sectional variability (channel depth) for a significant portion of the reach (> 33%). |

## *F10:* Structure of the channel bed

**DEFINITION**

A stream in natural conditions exhibits a heterogeneity of the bed and bars sediment size, structure and texture, except in some specific cases (i.e. confined bedrock channels or streams with fine bed sediment). The structure and heterogeneity of the channel bed sediment have several implications for the functionality of the bedload processes and flow resistance, and are extremely important for the aquatic habitats. This indicator takes into account possible alterations of the bed sediment, such as armouring, clogging, substrate outcrops or bed revetments, related to morphological adjustments (e.g. bed incision or excessive aggradation) or directly to human interventions (e.g. revetments). Armouring refers to the presence of a surface layer in which bed size is significantly greater than the sub-layer. Clogging refers to an excess of fine sediments (potentially linked to excessive soil erosion because of land use changes, or to alterations of hydrological regime) causing interstitial filling of the coarse sediment matrix and potentially smothering the channel bed ("blanket": Brierley and Fryirs, 2005, or "embeddedness": Sennatt et al., 2008).

| Spatial scale | |
|---|---|
| *Longitudinal*: Multiple sites - reach | *Lateral*: Channel |
| **Measurements**: Field survey | |

This indicator is applied to **confined** with a mobile bed as well as **partly confined and unconfined channels**. It **is not applied** to **bedrock and colluvial confined channels**, **sand-bed rivers**, because of their natural bed substrate homogeneity, and in the case of **deep, non-wadeable rivers**, as it is not possible to visually observe the substrate.

There are differences between the cases of confined channels and partly confined or unconfined channels. In the former case, armouring is not considered as an indicator of alteration, because normally confined channels with a mobile bed have a naturally strong heterogeneity of sediments. Therefore, armouring is assessed only in the case of partly confined and unconfined channels. For partly confined and unconfined channels, some heterogeneity of bed substrate size is also considered as normal, as a consequence of the variability of morphological units (bars, baseflow channels, riffles, pools), as well as in the same unit. However, a pronounced armouring is considered as an alteration (see below). Similarly, the presence of clogging can be normal in particular situations (e.g. in some of the pools or along a stream close to hillslopes composed of clay), but it is considered an alteration when it is evident and present in various portions of the reach.

A **field** evaluation is necessary for this indicator. The evaluation can start from a series of representative **sites** to ensure that various portions of the reach are assessed. In many cases, the assessment performed at a number of sites is sufficient to determine the class, but in more problematic cases (for example, in the case of contrasting evidence), a rapid reconnaissance along the whole reach may be necessary.

A quantitative assessment of armouring would require sediment sampling and measurements of the surface layer and sub-layer, which are beyond the scope of this procedure. Therefore **armouring**, as well as **clogging**, are **visually assessed**. An evaluation is necessary, at least along the visited sites, of the percentage in length of the portions of the reach altered by armouring or clogging. Clogging and/or armouring are not potentially occurring on the whole bed surface and along all the geomorphic units. For example, clogging is not potentially expected along units with relatively high flow velocity (e.g., rapids, steps), and armouring is also uncommon along units with low flow velocity (e.g., pools). Therefore, if a portion of the reach show evident armouring (or clogging) along most of the geomorphic units where this is potentially possible to occur, the entire length of this portion is considered as altered.

An additional element of alteration is **bedrock outcropping**. However, it requires careful evaluation, especially in the case of confined channels, where it is considered as alteration only when it is evidently related to bed-incision due to human causes, for example when there is evidence or information of a previous alluvial substrate completely removed due to bed incision. Even in the cases of partly confined and unconfined channels, an alteration is taken into consideration only when this is clearly related to bed-incision due to human causes, that is, in alluvial reaches with a mobile bed sufficiently far from the hillslopes. It must be excluded, however, in those cases with hillslopes not far from the channel and where the former can represent natural outcrops. When the bedrock outcropping is related to recent bed-incision due to human causes, this determines the assignation to class *C1* (occasional outcropping) or *C2* (widespread outcropping, i.e. >33%). Bedrock outcropping must be evaluated at the **reach scale**.

Finally, the widespread presence of **bed revetments** (>33%) determines the assignation to class *C2*. As for bedrock outcropping, this must be evaluated at the **reach scale**.

**EXTENDED ANSWERS**

| Typology | Confined |
|---|---|
| Range of application | Not evaluated for bedrock, colluvial or sand-bed rivers, or for deep rivers when it is not possible to observe the channel bed |
| A | Natural heterogeneity of bed sediments in relation to the different sedimentary units (steps, pools, riffles, etc.), with absence of or localized situations of clogging. |
| B | Evident clogging occurring along <50% of the reach length. |
| C1 | Evident and widespread clogging occurring along > 50% of the reach length, or occasional substrate outcrops (≤ 33% of the reach length) related to recent bed-incision of the alluvial substrate (for human causes). |
| C2 | Widespread substrate alteration by bed revetments (any type) (> 33% of the reach length), or widespread substrate outcrops (> 33% of the reach length) related to recent bed-incision of the alluvial substrate (for human causes). |

| Typology | Partly confined or unconfined |
|---|---|
| Range of application | Not evaluated for bedrock or sand-bed rivers, or for deep rivers when it is not possible to observe the channel bed |
| A | Natural heterogeneity of bed sediments in relation to the different sedimentary units (bars, channel bed, pools, riffles, etc.) and also within the same unit, with absence of or localized situations of armouring and/or clogging. |
| B | Evident armouring or clogging occurring along <50% of the length. |
| C1 | Evident and widespread armouring or clogging occurring along > 50% of the length, or occasional substrate outcrops (≤ 33% of the reach length) related to incision of the alluvial substrate. |
| C2 | Widespread substrate outcrops (> 33% of the reach length) due to incision of the alluvial substrate or widespread substrate alteration by bed revetments (any type) (> 33% of the reach length). |

## *F11:* Presence of in-channel large wood

**DEFINITION**

An evaluation is carried out to determine whether altered conditions exist compared to the expected presence of large wood along the reach. Large wood includes trees, trunks, branches, butts having a length > 1 m and diameter > 10 cm. This material has several effects on geomorphic-hydraulic processes, and has various implications for ecological processes (habitat diversity, input of organic matter, etc.). On the other hand, it is widely recognized that this material represents an important hydraulic hazard factor.

| Spatial scale | |
|---|---|
| *Longitudinal*: Multiple sites - reach | *Lateral*: Channel |
| **Measurements**: Field survey | |

The indicator is evaluated for both types of streams (**confined and partly confined - unconfined**), while is not applied in the case of areas of **tundra in northern Europe**, where vegetation is naturally absent. Given the high spatial and temporal variability of the quantity of wood material, it is not possible to define precise values for the number of woody elements to observe. A reach, or a portion of it, is evaluated as altered when the presence of wood is extremely limited or completely absent (approximately < 5 elements every 100 m of channel length).

The operator carries out the evaluation based on **field observations**. In some cases, the presence of wood can be altered only for a portion of the reach (for example where there has been a removal of wood not extended to the whole reach). Therefore field observations must be carried out on a sufficient number of sites in order to sufficiently assess the whole reach. When, in all the visited sites a significant presence of wood is observed, the reach can be assigned to class A. In the case that in one or more sites an absence (or extremely limited presence) of wood is noted, then an evaluation of the extent of the reach with absent wood is necessary to determine whether to assign the reach to class B or C (see extended answers). In some cases (very high resolution images), remote sensing can be useful, and the evaluation can be carried out for greater reach lengths and eventually at the reach scale.

The evaluation area includes the channel (including islands) and the banks (wood on the floodplain is not considered). Additional rules accounting for particular situations of natural wood scarcity concern the case of large rivers (bankfull width > mean tree height), relatively deep (mean bankfull depth > mean tree diameter), with few bars and/or boulders of great size. These reaches are considered as reaches of **"wood transport"**. This is the case of relatively large rivers with plane bed morphology (confined) or single-thread channels, where some large wood should be present along the banks, except in case of rocky banks and/or with natural absence of tree vegetation. In these latter cases, class *A* is assigned.

Lastly, the indicator is **not evaluated** for reaches **above the tree-line** or where riparian vegetation is completely absent due to natural factors in the reach and in the upstream reaches. The indicator is evaluated in reaches where the vegetation is locally absent (e.g. local hillslope banks), because a certain amount of wood is expected to be supplied from the upstream reaches.

**EXTENDED ANSWERS**

| | |
|---|---|
| Typology | All typologies |
| Range of application | Not evaluated above the tree-line and in streams with natural absence of riparian vegetation, such as in north-european tundra |
| A | Significant presence of large wood (plants, trunks, branches, butts) within the channel and/or on the banks along the whole reach. Or absence of large wood in case of reach of wood transport (bankfull width > mean tree height, bankfull mean depth > mean tree diameter, absence of significant obstacles, e.g. bars and large boulders). |
| B | Very limited presence or absence of large wood for ≤ 50% of the reach length |
| C | Very limited presence or absence of large wood for >50% of the reach length. |

## Vegetation in the fluvial corridor

The next two indicators (*F12* and *F13*) concern the woody and shrub **vegetation in the river corridor**. The latter includes the area extending from the channel to the hillslopes (or the old terraces), theoretically including the entire floodplain, and that is functional to the normal geomorphic processes (flow resistance, bank stabilization, wood recruitment, sediment trapping, etc.).

The presence of **emergent aquatic macrophytes** is also considered in some specific contexts (i.e. low-energy straight, sinuous, meandering and anabranching channels) where these plants are expected to occur in abundance. Aquatic emergent linear-leaved macrophytes are vascular plants that root into the river bed and margins but their canopy emerges vertically above the low flow water level, forming stands that present a significant flow resistance: with this term we consider in particular rushes and reeds. We exclusively consider aquatic linear-leaved emergent macrophytes in the evaluation of the aquatic vegetation (only in the indicator *F13*) because previous research has shown that this "plant morphotype" can have a sustained (year to year) morphological effect on channel morphology, by trapping, retain and reinforcing sediment (Gurnell et al., 2006, 2010; Gurnell, 2014) with the widely-occurring species, *Sparganium erectum,* being a particularly effective plant in modifying the hydromorphological properties of low energy river channels (Gurnell et al., 2013).

Only the geomorphic functioning of these types of vegetation are considered, and so their width and areal extent in the riparian zone and areal coverage within the active channel are the main considerations since these factors are the primary determinants of their level of interaction with the morphological processes of erosion, sedimentation and flooding. Commercial tree plantations (e.g. *Populus* sp., *Eucalyptus* sp., *Paulownia* sp., conifers etc.) are considered as partially functional, as they are characterized by lower tree densities than natural riparian forests and consequently do not fully perform their geomorphic functions. Therefore, lower scores are assigned to this type of vegetation. Other, low density, commercial plantations of woody vegetation (e.g. olive tree, grape vines, apple trees, etc.) are not considered as functional. However, non-commercial reforested areas that are characterized by higher tree densities, comparable to those of naturally-formed riparian woodland, are considered to be fully functional.

In order to be considered functional, woody vegetation should be fully connected to the relevant geomorphic processes (i.e. flooding, sediment erosion and deposition). Therefore, vegetation separated from the river by **artificial levées** is excluded, whereas vegetation bordering protected (artificially reinforced) river banks is taken into consideration because it can still be flooded allowing it to provide flow resistance, supply wood, and trap sediment. In the case of confined channels, **roads** interrupt this connection (similarly to the artificial levees for unconfined channels).

Indicators *F12* and *F13* are not applied **above the natural tree-line**. In Italy, for example, this limit is quite variable, (approximately around 1,800 ÷2,300 m a.s.l.) and, in many cases, grazing has lowered this limit: in such a case, it is considered as an alteration. The two indicators are not applied in the case of areas of **tundra in northern Europe**, where vegetation is naturally absent. Lastly, in the case of particular climatic and soil conditions such as in **Mediterranean regions**, dense woody vegetation may not develop within the river corridor, and so a sparse cover of trees and shrubs can be considered as functional vegetation.

## *F12:* Width of functional vegetation

**DEFINITION**

This indicator assesses the average width (or areal extension) of **functional riparian vegetation in the fluvial corridor** directly connected with the channel. In the case of confined channels, the functional width is evaluated up to a distance of 50 m from each bank, excluding the cases of near vertical hillslopes or where landslides are present, where woody vegetation may be naturally absent. In the case of partly confined and unconfined channels, the width of functional vegetation is evaluated as a function of channel width.

| Spatial scale | |
|---|---|
| *Longitudinal*: Reach | *Lateral*: Entire floodplain (partly confined / unconfined); Floodplain/ adjacent hillslopes (confined) |
| **Measurements**: Remote sensing | |

The evaluation is carried out by **remote sensing** and **GIS** analysis, by delimitating the woody/shrub vegetation in the river corridor, up to a limit of 50 m in the case of confined channels. The width includes the vegetation on both sides of the channel. Note that any islands present within the channel are included in the computation (even in the case of anabranching channels), considering their potential contribution in terms of flow resistance, sediment trapping and large wood delivery. In the case of partly confined channels, where the functional vegetation occupies the entire available width (i.e. the entire floodplain), class *A* is attributed to the reach even if the width of the functional vegetation is lower that *nW* (see table below).

**EXTENDED ANSWERS**

| | |
|---|---|
| **Typology** | All typologies |
| **Range of application** | Not evaluated above the tree-line and in streams with natural absence of riparian vegetation, such as in north-european tundra |
| **A** | A high width of functional vegetation:<br>for *confined channels*, connected functional vegetation occupying > 90% of hillslopes (50 m from each bank, excluding portions with rock or landslides) and the adjacent floodplain (if present). The functional vegetation includes woody tree or shrub species with significant cover (i.e. > 33% of the width). In Mediterranean regions, functional vegetation can only include spontaneous shrub species.<br>for *partly confined - unconfined channels*, connected functional vegetation with a total width (sum of the two sides) of at least *nW*, where *W* is the channel width, *n* = 2 for single-thread or anabranching channels, *n* = 1 for braided or wandering channels. The functional width includes either woody and shrub species, with a significant presence of the former (> 33% of the width |

| | |
|---|---|
| | occupied by woody vegetation). In Mediterranean regions, functional vegetation can only include spontaneous shrub species. |
| B | A medium width of functional vegetation:<br>for *confined channels*, connected functional vegetation occupying 33÷90% of hillslopes (50 m from each bank, excluding portions with rock or landslides) and the adjacent floodplain (if present). The functional vegetation includes woody tree or shrub species with significant cover (i.e. > 33% of the width).<br>Or, as in case A, but with largely prevailing shrub species (i.e. woody vegetation ≤ 33% of the functional width) except for specific climatic contexts (e.g. Mediterranean regions), where woody vegetation may not naturally develop.<br>for *partly confined - unconfined channels*, connected functional vegetation with a total width (sum of the two sides) between $0.5W$ and $nW$, where $W$ is the channel width, $n = 2$ for single-thread or anabranching channels, $n = 1$ for braided or wandering channels.<br>Or, as in case A, but where the width > $nW$ is determined by the presence of partially functional species (e.g. artificial plantations of *Populus* sp.), or in the case of largely prevailing shrub species (i.e. woody vegetation ≤ 33% of the functional width). |
| C | A limited width of functional vegetation:<br>for *confined channels*, connected functional vegetation ≤ 33% of hillslopes (50 m from each bank, excluding portions with rock or landslides), and of adjacent plain (if present). The functional vegetation includes woody tree or shrub species with significant cover (i.e. > 33% of the width).<br>Or, as in case B, but with largely prevailing shrub species (i.e. woody vegetation ≤ 33% of the functional width) except for specific climatic contexts (e.g. Mediterranean regions), where woody vegetation may not naturally develop.<br>for *partly confined - unconfined channels*, connected functional vegetation with a total width (sum of the two sides) ≤ $0.5W$ (any channel typology), where $W$ is the channel width.<br>Or, as in case B, but where the width > $0.5W$ is determined by the presence of partially functional species (e.g. artificial plantations of *Populus* sp.), or in the case of largely prevailing shrub species (i.e. woody vegetation ≤ 33% of the functional width). |

### *F13:* Linear extension of functional vegetation and presence of emergent aquatic macrophytes

**DEFINITION**

This indicator evaluates the longitudinal continuity of **functional vegetation along the banks**, as a percentage of the length covered by vegetation against the total length of the reach (both banks), and for any areal extension. The indicator refers to the functional vegetation in the river corridor zones external to the channel, therefore islands are not considered, except in the case of large islands separating anabranch channels in anabranching rivers. Lines of ornamental trees on the channel edge are considered as partially functional, and so they are treated in the same way as commercial plantations (see previous indicator).

In the case of some specific channel morphologies (i.e. low-energy straight, sinuous, meandering and anabranching channels) the evaluation of longitudinal continuity of functional vegetation along the banks is coupled with an evaluation of the presence of emergent aquatic macrophytes.

| Spatial scale | |
|---|---|
| *Longitudinal*: Multiple sites – reach | *Lateral*: Banks (riparian vegetation) - channel (aquatic vegetation) |
| **Measurements**: Remote sensing (riparian vegetation) - field survey (aquatic vegetation) | |

The evaluation of the **linear extension of riparian vegetation** is carried out by **remote sensing** and **GIS** analysis. The same delimitation of woody/shrub vegetation in the river corridor connected with the channel carried out for *F12* is used, measuring the length (sum of the two banks) in direct contact with the channel. This length is compared with the total potential length (sum of the two banks) where functional vegetation could be present (i.e. excluding portions of banks comprised of rock or affected by landslides). In the case of anabranching channels, the length is evaluated for all anabranch channels and the total potential length is the sum of the bank lengths of all the anabranches. When remote images are difficult to interpret (e.g. for confined channels), a **site** scale check may be required (e.g. to identify banks comprised of rock).

The evaluation of the **presence of emergent aquatic macrophytes** is considered exclusively in **low energy channel morphologies** (i.e. low-energy straight, sinuous, meandering, and anabranching channels). Where estimates are available, **unit stream power** can be used to support definition of the range of applicability of emergent aquatic macrophytes. Unit stream power is calculated as the product of *Qmed* (i.e. the median flood of the annual flood series), slope and specific weight of water, divided by the channel width. Following analysis of a national UK data set, it has been shown that to achieve a significant cover of emergent, linear-leaved aquatic macrophytes, unit stream power needs to fall below **a threshold of 60 W/m$^2$**: above this value these plants may be present but their abundance is likely to be low and their persistence at a particular location too short for a significant geomorphic effect (Gurnell et al., 2010, 2013; Gurnell, pers.comm.). The presence of emergent aquatic macrophytes is **not evaluated in large rivers** (although macrophytes may be important in side channels)**, in temporary streams** or **where the riparian vegetation canopy completely shades the entire channel** (i.e. where intense shade prevents the abundant growth of aquatic macrophytes). As a result of difference in the angle of incidence of solar radiation, shading by river banks and riparian vegetation can influence more strongly the presence of emergent aquatic macrophytes in central-northern Europe than in, for example, the Mediterranean region, so the geographical location of the study reaches has to be carefully considered. River widening and low water velocity due to flow regulation can lead to an abundant growth of these plants, but in these circumstances, the hydromorphological effect is to narrow the channel so that it becomes adjusted to the regulated flow regime. In extreme cases, the regulated flow regime is insufficient to maintain a functioning river channel, in which case, "choking" of the channel by macrophytes may ultimately lead to the formation of a wetland area rather than a narrowed channel. This raises the question of whether macrophytes may require management to artificially maintain a channelled flow.

When aquatic macrophytes are evaluated, an **emergent aquatic macrophyte class** (A or C) is assigned to each reach, mainly based on **field observations,** although remote sensing can provide an accurate assessment of entire reaches when only a low riparian tree cover is present and if the images were obtained in summer. The evaluation area is the river channel to the level of normal winter flow. Field observations have to be carried out on a sufficient number of sites to provide a reliable assessment for the whole reach, particularly in reaches where aquatic vegetation may be managed by cutting. **Case A** is attributed when a significant presence of emergent macrophytes is observed for > 50% of the reach length, while **case C** occurs when a very limited presence or absence of emergent aquatic macrophytes is observed for ≥ 50% of the reach length.

The assessments for riparian and aquatic vegetation are then combined to derive a **combined class** (A, B or C) of the indicator *F13* according to the matrix shown in Table 2.

**Table 2 Definition of the classes for the indicator *F13* in low energy rivers where the presence of emergent linear-leaved aquatic macrophytes is considered.**

<table>
<tr><th colspan="2" rowspan="2"></th><th colspan="3">Linear extension of riparian vegetation</th></tr>
<tr><td>A (>90%)</td><td>B (33÷90%)</td><td>C (≤33%)</td></tr>
<tr><td rowspan="2">Presence of emergent aquatic macrophytes</td><td>A (significant presence for > 50% of the reach length)</td><td>A</td><td>A</td><td>B</td></tr>
<tr><td>C (very limited presence or absence of emergent aquatic macrophytes for ≥ 50% of the reach length)</td><td>B</td><td>C</td><td>C</td></tr>
</table>

**EXTENDED ANSWERS**

| | |
|---|---|
| Typology | All typologies |
| range of application | Riparian Vegetation: Not evaluated above the tree-line and in streams with natural absence of riparian vegetation, such as in north-european tundra<br>Aquatic vegetation: It is evalauted only in low-energy straight, sinuous, meandering (or single-thread confined) or anabranching channels |
| A | Linear extension of connected functional (riparian) vegetation for > 90% of maximum available bank length (i.e. sum of both banks excluding those comprised of rock or landslides). Presence of either tree or shrub species (> 33% of the length of functional vegetation). In dry Mediterranean regions, functional vegetation may only include spontaneous shrub species. In the case of anabranching channels, the reach length is the sum of the lengths of the anabranches.<br>In low-energy straight, sinuous, meandering and anabranching channels, the condition of the riparian vegetation as described above (case A) is combined with a significant presence of emergent aquatic macrophytes for > 50% of the reach length (case A); or connected riparian vegetation extending for at least 33% of the available bank length (case B) in combination with a significant presence of aquatic emergent macrophytes for > 50% of the reach length (case A). |
| B | Linear extension of connected functional vegetation for a length of 33÷90% of maximum available length (i.e. sum of both banks excluding those in rock or landslides). In the case of anabranching channels, the reach length is the sum of the lengths of the anabranches.<br>Or, as in case A, but the extension > 90% is determined by the presence of partially functional species (e.g. industrial plantations of *Populus* sp.or rows for ornamental purposes), or in the case of shrub species largely prevailing (woody species < 33% of the length of the functional vegetation). |

| | |
|---|---|
| | In case of low-energy straight, sinuous, meandering and anabranching channels:<br>- linear extension of connected functional vegetation for a length > 90% of maximum available length (case A) and very limited presence or absence of emergent aquatic macrophytes for ≥ 50% of the reach length (case C);<br>Or<br>- linear extension of connected functional vegetation for a length < 33% of maximum available length (case C) and significant presence of aquatic emergent macrophytes for > 50% of the reach length (case A). |
| C | Linear extension of connected functional vegetation for a length of ≤ 33% of maximum available bank length (i.e. sum of both banks excluding those comprised of rock or landslides). In the case of anabranching channels, the reach length is the sum of the lengths of the anabranches.<br>Or, as in case B, but the extension > 33% is determined by the presence of partially functional species (e.g. industrial plantations of *Populus* sp. or rows for ornamental purposes), or in the case of shrub species largely prevailing (woody species < 33% of the length of the functional vegetation).<br>In case of low-energy straight, sinuous, meandering and anabranching channels, linear extension of connected functional vegetation for a length ≤ 90% of maximum available length (case B or C) and very limited presence or absence of aquatic emergent macrophytes for ≥ 50% of the reach length (case C). |

## *Artificiality*

## Upstream alteration of longitudinal continuity

The first four indicators of artificiality consider the alteration of the driving variables for channel morphology, which are water discharges and sediment transport. It is useful to conceptually separate the alterations of the same variables occurring upstream and within the reach. Indicators *A1* and *A2* are the only two concerned with the conditions existing upstream (catchment scale) of the analyzed reach, while the next two indicators *A3* and *A4* concern the alterations of the same characteristics, but within the reach.

For this purpose, in the case of a **structure** (e.g. a dam) **located at the boundary between two reaches** (e.g. between an upstream reach *n1* and a downstream reach *n2*), **conventionally the structure is assigned to the upstream reach**. In other terms, the effects of the structure are considered as alterations in the reach (by the indicators *A3* and *A4*) for the upstream reach *n1*, while they are accounted as upstream alterations (by the indicators *A1* and *A2*) for the downstream reach *n2.*

### *A1:* Upstream alteration of flows

**DEFINITION**

This indicator evaluates possible alterations of flow conditions which may have a significant effect on morphological processes. Therefore, the main emphasis is on channel-forming discharges and/or discharges with higher return intervals related to interventions at the catchment scale, such as dams, impoundment (i.e. water retention by weirs), discharge diversions or water abstractions, spillways, retention basins, etc.

Specific cases of alteration of low flows (release of constant flows downstream of dams) which may also have morphological effects are also considered.

The indicator does not directly evaluate the effect of these structures on sediment discharge, which is assessed by the following indicator (*A2*). This indicator also accounts for those structures which cause an increase, rather than a reduction, of the water discharge (e.g. water input from another basin or watercourse). In the case of a diversion where the water is returned to a downstream reach, only the river portion between the water diversion and the restitution is considered as altered. The indicator is not applied to the most upstream reach of a river, except when the water diversion occurs at the source.

| Spatial scale | |
|---|---|
| *Longitudinal*: Upstream catchment | *Lateral*: Entire floodplain (including recent terraces) |
| **Measurements**: Map layer of interventions, remote sensing | |

Identification of existing interventions having effects on discharges can be carried out by a map layer of interventions and remote sensing. This indicator also requires data and information about the management of the structures (e.g. dams) and their effects on discharges. This can be achieved from agencies in charge of the river management. Note that this type of information and hydrologic data collected at the catchment scale is an essential part of the **Phase 1** (*general setting-up*), and this knowledge is then used for all the reaches of a given catchment.

Also note that this indicator can be estimated starting from the data required to assess the alterations of the hydrological regime by specific indices (e.g. *IAHRIS*, *IARI*, *QM-HIDRI*, etc.), which generally provide a measure of the deviation between the observed hydrological regime and the natural regime (i.e. not only channel-forming and higher discharges) in the absence of human intervention. The index *IARI* is obtained, depending on available river discharge data quality and consistency, by comparing the daily and/or monthly discharges actually flowing through the cross section and the corresponding natural discharges. The integration of morphological and hydrological aspects allows for a complete definition and classification of stream hydromorphology.

To evaluate the indicator *A1*, **three broad classes of discharge** are considered (in order of importance in terms of morphological effects): (1) channel-forming discharges; (2) discharges with a return interval > 10 years; (3) flows below channel-forming discharges.

(1) **Channel-forming discharges**. These are intended as the discharges having the most relevant effects on channel morphology. A value of $Q_{1.5}$ is conventionally used here to represent the channel-forming discharge. However, the range of discharges with important effects on channel morphology can be widened to return intervals of the order of 10 years. In fact, in braided or wandering morphologies, there are different values which can affect channel form, with islands being modelled by discharges with return interval up to 10 years. Furthermore, in the case of steep and armoured mountain streams, only discharges with return intervals > 2÷3 years are in general able to determine relevant processes of sediment transport (except in the cases of natural high bedload supply), and the morphological channel configuration is determined by even higher discharges.

(2) **Discharges with return interval (*RI*) >10 years**. These also have relevant morphological and hydraulic effects, although their effect on channel morphology is lower than the channel-forming discharge, because of their lower frequency. There are interventions which only have an effect on discharges with a high return interval, as they are designed to start working only above a given threshold (e.g. spillways, retention basins, some dams).

(3) **Flows below channel-forming discharge.** This class includes the range of discharge which varies from low-flow conditions to small or moderate flow events

below channel-forming flows. Low flows below threshold conditions of erosion and sediment transport are considered to have negligible effects on channel morphology, and therefore alterations to these flows are not evaluated by this indicator but need to be assessed separately by a specific index of hydrological regime alteration (e.g. *IAHRIS*, *IARI*, *QM-HIDRI*, etc.). A notable exception, which is accounted for by indicator *A1*, is represented by the **water regulation by dams**, i.e. the release of a relatively constant discharge, **higher than natural flow**. This case is particularly applicable to rivers characterized by a typical Mediterranean hydrological regime (i.e. high flow variability and low-water level during the summer). For such cases, some authors observed that the increase of low-flow discharge dams and reservoirs may have a geomorphological impact on channel geometry and dynamics (Johnson, 1994; Magdaleno and Fernandez, 2013; Garofano Gomez et al., 2013; Petts and Gurnell, 2013). In fact, the increase of the water level during the summer in rivers which are normally dry or with very low flows, can induce a rise in the water table and promote vegetation encroachment across the channel, promoting channel narrowing.

Data needed for estimating the discharges with given return intervals, and information to evaluate the effects of interventions on such discharges, are often not available. Therefore, **two procedures** can be considered, as follows.

**1. Data available**

A more rigorous and quantitative procedure is only applied, where data is available, to the evaluation of alterations on channel-forming discharges and/or higher. Possible alterations of flows below channel-forming discharge, restricted to the specific case of prolonged release of increased flows downstream from a dam, are evaluated only qualitatively.
First, it is necessary to evaluate if and how much any intervention existing upstream in the catchment produce alterations on the channel-forming discharges and/or discharges with return interval >10 years.

(1) **Channel-forming discharges**. Estimation of $Q_{1.5}$ *ante* or *post operam* (or of other $Q$ with *RI* between 1.5 and 10 years) can be obtained by a statistical analysis of a sufficiently long series of maximum annual peak discharges, from the closest gauging station to the reach, or on the basis of rainfall – runoff models or models of regionalization of discharges (these estimations are often available at the public agencies responsible for the river management). Normally, this analysis is performed only on the $Q_{1.5}$, but in some cases (e.g. braided rivers or mountain streams) further analysis on discharges with *RI* = 10 years may be necessary. When there are significant changes (> 10%) in these discharges due to artificial interventions, the reach is assigned to class *C*.
   - *Example*. $Q_{1.5}$ = 300 m$^3$/s and a reservoir existing upstream has the effect of reducing this discharge by about 60 m$^3$/s.

(2) **Discharges with *RI* > 10 years**. In the case of upstream interventions affecting this class of discharge and producing significant changes (> 10%), the reach is assigned to class *B* (even in case no changes in the channel-forming discharge occur).
   - *Example*. Presence of a retention basin upstream designed to work only for discharges with *RI* > 20 years, and producing a reduction of 30 m$^3$/s, compared to a $Q_{20}$ estimated to be about 150 m$^3$/s.

(3) **Flows below channel-forming discharge.** In the case of prolonged releases of increased flows downstream a dam, specifically during the dry seasons of Mediterranean regime-dominated rivers, producing evident effects on vegetation and channel morphology, the reach is assigned to class *B*.

Should any of the previous alterations be assessed, the reach is assigned to class *A*. The logical sequence of assessment is summarised in Table 3 and Figure 2.

**Table 3 Definition of the classes for the indicator A1.**

| | $\Delta Q_{1.5\text{-}10}$ | $\Delta Q$ (*RI* > 10 years) | Low flows |
|---|---|---|---|
| A | < 10% | < 10% | No morphological effects |
| B | < 10% | > 10% and/or increased low flows downstream dam | |
| C | > 10% | Any case | Any case |

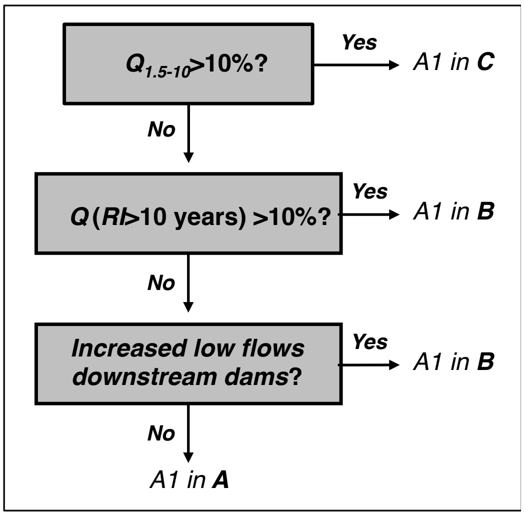



**Figure 2 Flow chart of the indicator A1.**

### <u>EXTENDED ANSWERS</u>

| Typology | All typologies |
|---|---|
| A | Absence of interventions altering water discharge (dams, spillways, diversions, retention basin, etc.) or interventions however with no significant effects (induced changes ≤ 10%) on channel-forming discharges and on discharges with *RI* > 10 years. |
| B | Presence of interventions (dams, spillways, diversions, retention basin, etc.) having significant effects (induced changes > 10%) on discharges with *RI* > 10 years, but with no significant effects (≤ 10%) on channel-forming discharges.<br>Or release of increased low flows downstream dams during the dry seasons of Mediterranean regime-dominated rivers, producing evident effects on vegetation and channel morphology. |
| C | Presence of interventions (dams, spillways, diversions, retention basin, etc.) having significant effects (induced changes > 10%) on channel-forming discharges. |

## <u>2. Data not available</u>

In such a case, a **simplified procedure** is adopted that is based on the typology of intervention and on available information about its use (e.g. dam for hydroelectric production or for retention purposes), described as follows. Cases of prolonged releases of increased flows downstream a dam are evaluated in the same way as for the previous procedure,

**EXTENDED ANSWERS**

| **Typology** | All typologies |
|---|---|
| A | Absence of interventions altering water discharge, or existence of interventions, but with no effects on channel-forming discharge and on discharges with higher return intervals (e.g. limited water abstraction for irrigation or other uses). |
| B | Presence of dams (watershed area > 5% of the reach drainage area) with reduction of peak discharges, or spillways or retention basins functioning only for infrequent discharges (*RI* > 10 years).<br>Or release of increased low flows downstream dams during the dry seasons of Mediterranean regime-dominated rivers, producing evident effects on vegetation and channel morphology. |
| C | Presence of dams (watershed area > 5% of the reach drainage area) with reduction of peak discharges, or spillways or retention basins functioning for relatively frequent discharges (*RI* < 10 years), or existence of diversions of medium – large size with water restitution downstream the reach, or diversions such to induce a significant effect on channel-forming discharge. |

## *A2:* Upstream alteration of sediment discharges

**DEFINITION**

An indirect evaluation of the alterations in sediment transport is obtained based on the existence in the catchment of blocking structures of bedload interception (dams, check dams, weirs), accounting for their drainage area in relation to the reach drainage area. The indicator does not consider hillslope interventions (e.g. reforestation, landslide stabilisation, etc.). Major blocking structures, such as dams, are evaluated here only for their effect on sediment trapping (impacts on flow regime are considered in *A1*). Interception of the bedload and river fragmentation may have significant effects on the reach's morphological dynamics. This may cause a reduction of depositional features (e.g. bars), inducing erosion processes and eventually promoting instability conditions.

| **Spatial scale** | |
|---|---|
| *Longitudinal*: Upstream river network | *Lateral*: Channel |
| **Measurements**: Map layer of interventions, remote sensing | |

The degree of alteration in sediment discharges is evaluated as a function of two aspects: (1) the type of structure and its impact on bedload (i.e. full interception or partial interception, depending on the sediment filling); (2) the ratio between the drainage area upstream of the structures and the drainage area of the watershed at the section of the reach closure. Furthermore, some differences exist depending on the physiographic context (mountain areas, hilly areas, lowland).

Concerning the **typology of structures**, the following three cases are considered:

- **(*T1*) Dams**. They create a complete and permanent (in a future perspective) interception and trapping of bedload (except in the cases of measurements of sediment release downstream, which are accounted for).
- **(*T2*) Structures with total interception of bedload**. These determine (or determined) a complete interception (e.g. check dams of a significant size not filled by sediment), but their impact is considered to be lower than dams, because of their temporary effect (until they are filled).
- **(*T3*) Structures with partial or no interception of bedload**. These are smaller sized structures, often with the purpose of bed stabilization rather than sediment

retention, or also bigger structures (check dams) with the purpose of sediment retention but now completely filled by sediment.

The indicator does not intend to evaluate the alteration of the exact amount of the sediment discharge entering into a reach, but rather to assess whether a significant change of the potential sediment supply from the upstream area occurred. Concerning the **drainage area** upstream of the structures as opposed to that upstream of the reach, the following classes are considered:

(1) ***As* ≤ 5% *Ar***, that is the area upstream the from structures (*As*) is smaller than 5% of the area upstream of the reach (*Ar*) (e.g. a dam upstream with a drainage area of 40 $km^2$ compared to a drainage area of the reach of 500 $km^2$);

(2) 5**% *Ar* < *As* ≤ 33% *Ar***, that is the area upstream from the structures (*As*) is between 5% and 33% of the area upstream the reach (*Ar*) (e.g. a dam upstream with a drainage area of 40 $km^2$ compared to the reach's drainage area of 400 $km^2$);

(3) **33% *Ar* < *As* ≤ 66% *Ar***, that is the area upstream from the structures (*As*) is between 33% and 66% of the area upstream of the reach (*Ar*) (e.g. a dam upstream with a drainage area of 120 $km^2$ compared to the reach's drainage area of 200 $km^2$);

(4) ***As* > 66% *Ar***, that is the area upstream from the structures (*As*) is > 66% of the area upstream from the reach (*Ar*) (e.g. a dam upstream with a drainage area of 150 $km^2$ compared to the reach's drainage area of 200 $km^2$);

(5) The structure is located at the **upstream limit of the reach**.

Some differences in the evaluation occur, depending on the physiographic context, described as follows.

**1. Mountain areas**

Structures included in the **category *T2*** are **check dams with total sediment retention** (retention check dams: usually of large dimensions). Usually these structures are characterized by a small reservoir immediately upstream. Included in this category are also **abstraction weirs** of **relevant size** (in the order of various meters), which are **not filled**, and which have the effect of a temporary complete interception (until filling) of bedload.

Structures included in the **category *T3*** can be identified with **filled retention check dams**, **open check dams**, and **consolidation check dams**. The latter are considered only when they are a long **sequence of stepped check dams**, determining the stabilization of the longitudinal bed profile. The drainage area is referred to the check dam furthest downstream. Therefore, isolated consolidation check dams that are unable to significantly reduce the upstream sediment supply are not considered.

Assignation to the alteration class as a function of typology and drainage areas is reported in Table 4.

**Table 4 Definition of classes in mountain areas.**

| As/Ar<br>Typology | | 5÷33% | 33÷66% | > 66% | Upstream limit |
|---|---|---|---|---|---|
| (*T1*) | Dams | *B1* | *B2* | *C1* | *C2* |
| (*T2*) | Check dams with total sediment retention | *A* | *B1* | *B2* | *B2* |
| (T3) | Filled or open check dams or sequence of consolidation check dams | *A* | *A* | *B1* | *B1* |

## 2. Hilly and lowland areas

Structures included in the **category *T2*** can be identified with **consolidation check dams or abstraction weirs** of **relevant size** (in the order of several meters), which are **not filled**, and which have the effect of temporary complete interception (until filling) of bedload.

Structures in the **category *T3*** include **consolidation check dams or abstraction weirs**, but of a **smaller size**, or of a bigger size but **filled** with sediment.

Assignation to the alteration class as a function of typology and drainage areas is reported in Table 5.

**Table 5 Definition of classes in hilly or lowland areas.**

| As/Ar<br>Typology | 5÷33% | 33÷66% | > 66% | Upstream limit |
|---|---|---|---|---|
| (*T1*) Dams | *B1* | *B2* | *C1* | *C2* |
| (*T2*) Consolidation check dams or abstraction weirs (big in size) with complete interception | *A* | *B1* | *B2* | *B2* |
| (*T3*) Consolidation check dams or abstraction weirs with partial or no interception (or small in size) | *A* | *B1* | *B1* | *B1* |

**Measures of sediment release or removal**

In the case of **measures of sediment release downstream from a dam** (or other structure), the score is reduced according to the following rules (in any physiographic context):

(1) Measures allowing for the flux *of all bedload downstream* (complete by-pass): two classes lower are assigned (e.g. from *C2* to *B2*, or from *B1* to *A*).

(2) Measures allowing for a *high but not total bedload flux downstream*: a class lower is assigned (e.g. from *C2* to *C1*).

Vice versa, if the maintenance agency in charge of a structure carries out a periodic **sediment removal upstream from a check dam** (that is not released downstream) in order to prevent it from filling completely, the structure is considered as causing a complete interception of bedload (*T2*).

To determine the final class for this indicator, the following rules need to be considered:

1. The indicator is not applied for the most upstream reach of a river, unless relevant structures of sediment interception (e.g. sequences of check dams) are located further upstream.
2. In the case of more than one structure in the upstream catchment, the structure with the highest score is considered.
3. In the case of a natural barrage and a resulting lake (e.g. landslide dams, etc.), upstream artificial interception structures are not considered in the evaluation of reaches downstream from the lake.

Identification of existing structures can be carried out using the map layer of interventions (when available) and remote sensing. Note that this type of information concerning existing crossing structures at the catchment scale is an essential part of the **Phase 1** (*general setting*). Information on the degree of structure filling, should it be necessary to discriminate between two classes, can also be acquired from a map layer of interventions, from management agencies, or directly from field surveys. In general, it is recommended to proceed moving progressively upstream, and starting from the structures with the highest score, in order to acquire the information strictly necessary for the determination of the final score. The logical scheme is reported in Figures 3 and 4.

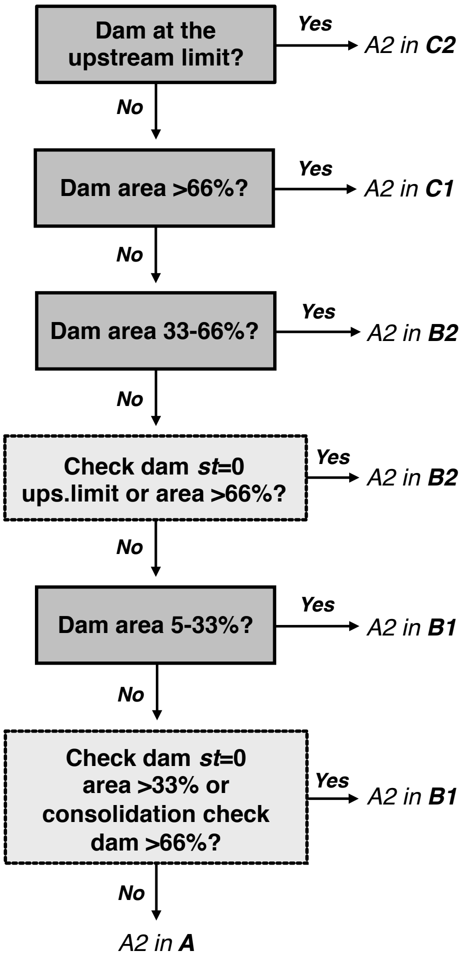



**Figure 3 Flow chart of the indicator *A2* for the *mountain areas* (*st* = sediment transport).**

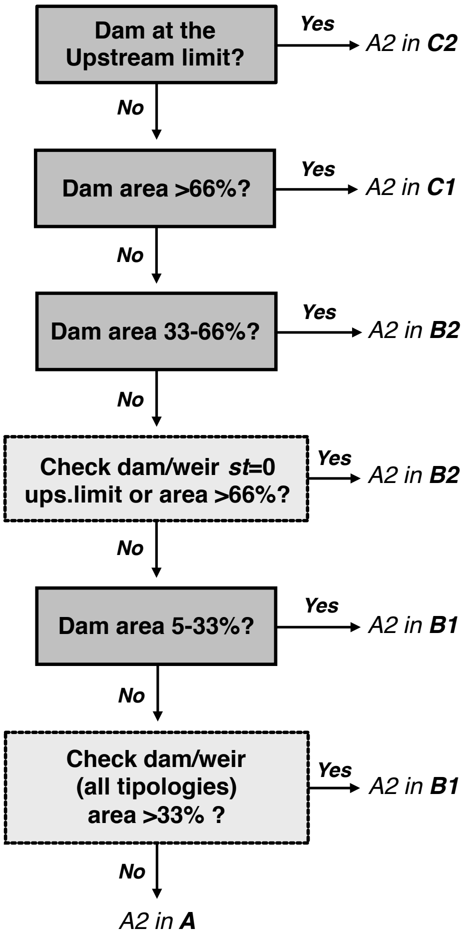



**Figure 4 Flow chart of the indicator *A2* for the *hilly – plain areas* (*st* = sediment transport).**

**EXTENDED ANSWERS**

| Typology | All typologies |
|---|---|
| A | Absence of structures that can alter the normal flux of sediment along the hydrographic network, or presence of weirs and/or dams but with no significant effects.<br>Dams are considered as not significant when *As* ≤ 5% *Ar*, i.e. the area upstream from the structures (*As*) is lower than 5% of the area upstream from the reach (*Ar*). Other interception structures are considered as not significant when *As* ≤ 33% *Ar*. |
| B1 | Presence of a dam (*any physiographic context*) for 5% *Ar* < *As* ≤ 33% *Ar*.<br>*Mountain areas*: one or more check dams not filled for 33% *Ar* < *As* ≤ 66% *Ar*, or one or more open or filled check dams or a sequence of consolidation check dams for *As* > 66% *Ar*.<br>*Hilly or plain areas*: one or more consolidation check dams or abstraction weirs with complete interception (large sizes) for 33% *Ar* < *As* ≤ 66% *Ar*, or one or more consolidation check dams or abstraction weirs with partial or no interception for *As* > 33% *Ar*. |
| B2 | Presence of a dam (*any physiographic context*) for 33% *Ar* < *As* ≤ 66% *Ar*.<br>*Mountain areas*: one or more check dams not filled for *As* > 66% *Ar* or at the upstream reach limit.<br>*Hilly or plain areas*: one or more consolidation check dams or abstraction weirs with complete interception (large sizes) for *As* > 66% *Ar* or at the upstream reach limit. |
| C1 | Presence of a dam (*any physiographic context*) for *As* > 66% *Ar*. |
| C2 | Presence of a dam at the upstream reach limit (*any physiographic context*). |
| ***Measures of sediment release downstream****: in case of measures allowing for the flux of all bedload downstream (complete by-pass), the structure is assigned to two classes lower. In case of measures allowing for a high but not total bedload flux downstream, the structure is assigned to one class lower.* | |

## Alteration of longitudinal continuity in the reach

### *A3:* Alteration of flows in the reach

**DEFINITION**

This is evaluated in the same way as *A1*, but in this case it refers to interventions along the reach. Interventions include spillway, flow diversions or water abstraction, and retention basins. Dams are excluded because they are necessarily identified with a limit of reach, therefore their effects in terms of alteration of discharge are necessarily evaluated in the reach downstream. Note that other structures too, which have a strong discontinuity on water discharge should be defined as the limits between two reaches (see Step 4: other discontinuities during the segmentation), therefore *A3* is rarely applied to this type of structure.

| Spatial scale | |
|---|---|
| *Longitudinal*: Reach | *Lateral*: Entire floodplain (including recent terraces) |
| **Measurements**: Map layer of interventions, remote sensing | |

Identification of existing structures can be carried out by remote sensing, whereas the information required to assign a reach to a class should be obtained by a map layer of interventions, or directly by the agencies in charge of the structure management, indicating location, type and operational methods. All the considerations made for *A1* are applied to this indicator, including two procedures (data available or not available), as follows.

**1. Data available**

**EXTENDED ANSWERS**

| Typology | All typologies |
|---|---|
| A | Absence of interventions altering water discharges (spillways, diversions, retention basin, etc.) or interventions but with no significant effects (induced changes ≤ 10%) on channel-forming discharges and on discharges with *RI* > 10 years. |
| B | Presence of interventions (spillways, diversions, retention basin, etc.) having significant effects (induced changes > 10%) on discharges with *RI* > 10 years, but with no significant effects (≤ 10%) on channel-forming discharges. |
| C | Presence of interventions (spillways, diversions, retention basin, etc.) having significant effects (induced changes > 10%) on channel-forming discharge. |

**2. Data not available**

**EXTENDED ANSWERS**

| Typology | All typologies |
|---|---|
| A | Absence of interventions altering water discharges or existence of interventions, but with no effects on channel-forming discharges and discharges with higher return intervals (e.g. limited water abstraction for irrigation or other uses). |
| B | Presence of spillways, diversions or retention basins functioning only for infrequent discharges (*RI* > 10 years). |
| C | Presence of spillways, diversions or retention basins functioning also for relatively frequent discharges (*RI* < 10 years), or existence of diversions of medium – big size with water restitution downstream the reach, or diversions such to induce a significant effect on channel-forming discharge. |

### *A4:* Alteration of sediment discharge in the reach

**DEFINITION**

This indicator is based on the typology and frequency of blocking structures intercepting bedload along the reach (check dams, weirs, diversion structures, etc.) or even other structures causing its alteration (e.g. retention basins, dam downstream, bed consolidation) by producing a partial sediment trapping or bedload reduction induced by a decrease in bed slope. The indicator does not refer to hillslope interventions (e.g. reforestation, landslide stabilisation, etc.).

| Spatial scale | |
|---|---|
| *Longitudinal*: Reach | *Lateral*: Channel |
| **Measurements**: Map layer of interventions, Remote sensing, Field survey | |

In the case of a **dam located at the downstream limit of the reach**, as previously explained, its effects in terms of bedload interceptions are considered in the downstream reach (indicators *A2* and *F1*). However, the dam also alters the normal bedload flux for the portion of the reach immediately upstream from the structure by decreasing the flow velocity and inducing sedimentation. If the artificial reservoir created by the dam is of a relevant size, it will not be subject to the assessment procedure (because the stream will have completely changed its original characteristics). Relevant size is normally intended to be equivalent to the spatial scale of a site (i.e. single-thread channels: length not less than 10 times the channel width; multi-thread, wide channels: minimum length to the order of 500 m). For reservoirs of a smaller size, these are included within the stream reach.

**Retention check dams** are high structures (up to 10 m) aiming to trap sediment and wood, commonly occurring in mountain areas. Check dams intercept all the material until they are completely filled. In this case, and in the absence of sediment removal, an equilibrium bed profile with a decreased bed slope tends to be reached, inducing coarse sediment deposition. Note that a check dam is usually associated to a boundary between two reaches, except in the case of a sequence of close check dams which may be included in the same reach to avoid excessive river segmentation. During the last decades, **open check dams** have been increasingly used, allowing the transport downstream of bedload of smaller grain size.

For the large structures described so far, definition of classes is simply based on the **presence/absence** of one (or more) of these structures along a reach, and not on their number or frequency (i.e. the presence of one structure along a reach of any length is sufficient for the assignation of the reach to a given class).

**Consolidation check dams** are not designed to intercept sediment and wood, but to decrease the intensity of the bedload transport and the effect of erosion through a reduction in bed slope. In this case, several structures are positioned along a given reach. The effect of these structures on channel morphology depends on the combination of their distance and height (i.e. the difference in elevation between structures) compared to the total difference in elevation within the reach. However, the information on structure height is difficult to obtain, therefore the indicator only refers to the **density** of structures along a reach (i.e. number per reach km), but differentiates the degree of alteration depending on bed slope. In fact, a transverse structure in a steep channel generally produces a smaller upstream effect compared to a channel with a relatively low slope, where the effect may occur for long distances upstream (hundreds of meters).

Finally, **instream retention basins** and **abstraction weirs**, which can partially intercept the sediment transport, are also considered in this indicator (note that in the case of channels with bed slope $S>1\%$, retention basins are considered as open check dams, whereas in channels with bed slope $S\leq1\%$ they are counted together with consolidation check dams and weirs).

All the structures can easily be identified by remote sensing, except in the case of small and confined channels (where very high resolution aerial photos are not available). In these cases, a map layer of interventions and/or field survey are required.

**EXTENDED ANSWERS**

| Typology | All typologies |
|---|---|
| A | Absence of any type of structures altering sediment discharges: there are no structures in the reach aimed to intercept sediment and wood (check dams, abstraction weirs, etc.) or which cause an alteration of sediment discharges (retention basins, dam downstream) although not designed for this purpose. |

| | |
|---|---|
| B | *Steep channels (bed slope S>1%):* consolidation check dams/weirs with relatively low density (≤ 1 every 200 m on average in the reach) and/or one or more open check dams (including instream retention basins).<br>*Channels with bed slope S≤1%:* consolidation check dam and/or abstraction weirs (including instream retention basins) with relatively low density (≤ 1 every 1000 m on average in the reach). In the case of anabranching channels, the length of the reach is the sum of the lengths of the anabranches. |
| C | *Steep channels (S>1%):* consolidation check dams/weirs with high density (>1 every 200 m on average in the reach) and/or one or more retention check dams.<br>*Channels with S≤1%:* consolidation check dams and/or abstraction weirs (including instream retention basins) with high density (>1 every 1000 m on average in the reach)<br>Or presence of a dam and/or artificial reservoir at the downstream reach limit (*any physiographic context*). |
| *Additional scores*<br>*If the total density of transversal structures, including bed sills and ramps (see A9) is very high, i.e. > 1 every 150 m in steep channels (S>1%), or >1 every 750 m in channels with S≤ 1%, add 6.*<br>*If the total density of transversal structures, including bed sills and ramps (see A9) is extremely high, i.e. > 1 every 100 m in steep channels (S>1%), or >1 every 500 m in channels with S≤ 1%, add 12.* | |

## A5: Crossing structures

**DEFINITION**

This accounts for the presence and frequency of crossing structures, including bridges, fords, and culverts, which may reduce or intercept sediment and wood transport. Only **bridges** which interfere with the fluvial corridor are considered, i.e. those bridges with some artificial element (piers or abutment) in the channel or adjacent plain, or which potentially interfere with water fluxes although only in occasion of exceptional flood events. Bridges that are completely unrelated to the fluvial corridor are not counted (e.g. a viaduct crossing a valley markedly higher than the channel and with piers and/or abutments standing directly on hillslopes). Regarding **fords**, only those with fixed crossing structures are accounted for here (i.e. dirt roads are not considered), because of their partial influence on bedload (coarse sediment). Finally, the cases where streams cross underground urban areas are considered as **culverts**. They have effects on channel cross-sections and lateral continuity similar to a crossing structure, while the additional alterations associated to a culvert (fixed banks, bed revetments) are evaluated separately through the indicators *A6* and *A9*.

| **Spatial scale** | |
|---|---|
| *Longitudinal*: Reach | *Lateral*: Channel |
| **Measurements**: Remote sensing, topographic maps, field survey | |

All these structures can easily be identified by remote sensing, except for culverts, which may require more detailed analysis using topographic maps and/or field checks. As for other indicators of artificial elements, this indicator evaluates the **number of crossing structures** along a reach rather than their effect.

**EXTENDED ANSWERS**

| Typology | All typologies |
|---|---|
| A | Absence of crossing structures (bridges, fords, culverts). |
| B | Presence of some crossing structures (≤ 1 every 1000 m on average in the reach).<br>In the case of anabranching channels, the reach length is the sum of the lengths of the anabranches. |
| C | Presence of many crossing structures (> 1 every 1000 m on average in the reach). |

## Alteration of lateral continuity

### *A6:* Bank protections

**DEFINITION**

Various types of bank protection are considered which alter the supply of sediment and wood from lateral channel mobility, including both hard bank reinforcement (walls, rip-raps gabions, groynes), and soft reinforcement (bioengineering).

| Spatial scale | |
|---|---|
| *Longitudinal*: Reach | *Lateral*: Banks |
| **Measurements**: Map layer of interventions, remote sensing, field survey | |

Only bank protections along the bank lines (which are the limits of the bankfull channel) or in the close surroundings are considered: bank protections built in past periods, at present far from the channel and therefore having no immediate effects on channel mobility are not assessed (they may be considered in the indicator *F5*, having the effect of limiting the erodible corridor).

Analysis from remote sensing does not always allow the identification of this type of structure, especially when they have been built in the past and are partly covered by riparian vegetation. The integration of remote observations with the map layer of interventions and/or field checks is recommended.

The indicator is based on the **percentage of protected banks** over the total length (sum of both banks), where the latter is defined in a GIS (for simplicity, it may be assumed to correspond to twice the reach length measured along the centreline). In the case of anabranching channels, the total bank length is the sum of both banks for each anabranch.

A particular case is that of the **groynes**, because they are placed perpendicular to the bank. Similarly to the previous rule, only groynes in contact or within the channel are considered (external groynes are considered in the indicators *F5*). In the latter case, an evaluation of the greater size between the groyne width and the protruding length is obtained (generally from aerial photos, and eventually from field check). In the case of groynes with the outer limit corresponding to the bank edge, their protruding length is equal to zero and therefore they have no effects for this indicator. Note that the indicator only evaluates the presence of groynes in terms of protected bank length, and not in terms of the magnitude of their effects (e.g. distance of influence).

**EXTENDED ANSWERS**

| Typology | All typologies |
|---|---|
| A | Absence or localized presence of bank protections, i.e. for a length ≤ 5% total length of the banks (sum of both banks). In the case of anabranching channels, the total bank length is the sum of both bank lengths for each anabranch. |
| B | Presence of protections for ≤ 33% total length of the banks (sum of both banks). |
| C | Presence of protections for > 33% total length of the banks (sum of both banks). |
| *Additional scores*<br>*In the case of bank protections along >50% of total length of the banks, add 6.*<br>*In the case of bank protections along >80% of total length of the banks, add 12.* | |

## *A7:* Artificial levées

**DEFINITION**

This indicator accounts for the presence and position of artificial levées (or embankments). They have an effect on the lateral hydrological continuity impeding the natural flooding of areas adjacent to the river. It is based on their longitudinal continuity and distance from the channel. Bank protections or embankments (evaluated in *A6*) with a height greater than the floodplain level are also evaluated by this indicator, as well as all those artificial infrastructures (e.g. roads) which also functions as a levée. On the other hand, artificial levées which also function as bank protection are also accounted for by the indicator *A6*.

| Spatial scale | |
|---|---|
| *Longitudinal*: Reach | *Lateral*: Entire floodplain (including recent terraces) |
| **Measurements**: Remote sensing, topographic maps, field survey, map layer of interventions | |

The indicator is applied only to **partly confined and unconfined channels**, because artificial levées are typically present in the floodplain (artificial levées in confined channels are infrequent and have no significant effect on the hydrological lateral continuity).

This indicator is mainly evaluated by remote sensing, supported by topographic maps. In the case of bank protections which function as levées, integrating the evaluation with a field survey and/or by consulting the map layer of interventions is recommended.

Regarding the **length**, the percentage of the artificial levée's length over the total length of the banks is considered (similarly to the previous indicator) though, in this case, the length of banks directly in contact with hillslopes is excluded. Regarding the **distance**, three possible cases are considered: (1) "*set-back levées*": in case of distance > of the mean channel width (*W*); (2) "*close*": in case of distance ≤ *W*; (3) "*bank-edge levées*": when they are immediately in contact with the top of the bank, or maximum at a distance of the same order of magnitude as the bank height. The distance here is considered to account for the effects of levées on the lateral channel mobility and on habitat diversity, rather than in terms of hydraulic risk. Selection of the class is made according to the extended answers and Table 6. Note that the calculation is made separately for the two river sides: e.g. in the case of a left bank with 100% in contact and a right bank with 20% in contact and 80% close, the total in the reach will be 60% in contact and 40% close.

In the case of **two artificial levée systems**, the distance will be referred to the levées closest to the channel. In the case of **anabranching channels** with multiple artificial levée systems (e.g. one for each single anabranch), the three cases must be applied to each single anabranch and the total bank length is the sum of both banks for all anabranches.

**Table 6 Definition of classes as a function of the length of bank-edge and close levées (in % over the total length of both banks).**

| Class | Sum of bank-edge and close [%] | bank-edge [%] |
|---|---|---|
| A | 0÷10 | 0÷10 |
| B | 10÷90 | 0÷50 |
| | 90÷100 | 0÷33 |
| C | 50÷90 | 50÷90 |
| | 90÷100 | 33÷100 |

**EXTENDED ANSWERS**

| Typology | Partly confined or unconfined |
|---|---|
| A | Absent or set-back levées (i.e. distance > *W*) for any length, or localized presence of close and bank-edge levées (≤ 10% of the total length of the banks). In the case of anabranching channels, each anabranch must be evaluated and the total bank length is the length of both banks for all anabranches. |
| B | The sum of close and bank-edge levées is > 10% of the total length of the banks, including the following cases (excluding banks directly in contact with hillslopes): (*a*) sum of close levées and bank-edge levées ≤ 90% of which bank-edge levées ≤ 50%; (*b*) sum of close levées and bank-edge levées > 90% of which bank-edge levées ≤ 33%. |
| C | The sum of close and bank-edge levées is > 50% of the total length of the banks, including the following cases (excluding banks directly in contact with hillslopes): (*a*) sum of close levées and bank-edge levées ≤ 90% of which bank-edge levées > 50% and ≤ 90%; (*b*) sum of close levées and bank-edge levées > 90% of which bank-edge levées > 33%. |
| *Additional scores*<br>*In the case of artificial bank-edge levées > 66% add 6.*<br>*In the case of artificial bank-edge levées along > 80% of total length of the banks) add 12.* | |

## Alteration of channel morphology and/or substrate

These indicators include other categories of artificial elements and interventions not considered by previous indicators, which have specific effects on channel morphology and/or on bed substrate. Note that also other structures included in previous indicators may have effects on channel morphology (e.g. bank protections may cause a reduction in channel width, check dams may cause the variation of the bed configuration and substrate, etc.).

### *A8:* Artificial changes of river course

**DEFINITION**

This indicator accounts for artificial past changes in the river course (recent or in historical periods). It has to be remarked that this indicator does not require a historical research of artificial channel changes, which would be out of the scope of this evaluation, but only well known and relevant changes should be considered (e.g. meander cutting, change of position of river mouth, etc.). This kind of artificial changes of the river course may have altered the natural channel morphology and modified natural geomorphological and hydraulic processes, with resulting loss of habitats.

| Spatial scale | |
|---|---|
| *Longitudinal*: Reach | *Lateral*: Entire floodplain (including recent terraces) |
| **Measurement**: Historical sources and/or remote sensing | |

The indicator is applied by remote sensing (e.g. identification of abandoned channel forms in the floodplain) with the support of historical sources (to verify whether or not changes were artificial). The indicator does not include artificial variations which maintain the river course in its original position although varying the channel size (e.g. direct interventions of channel narrowing, channelization).

The indicator is applied only to **partly confined and unconfined** channels. In the case of confined channels, artificial changes in the river course are infrequent and usually only concern limited portions of the channel. To determine the classes *B* or *C* the indicator evaluates the length of the reach interested by the artificial change in river course compared to the total reach length.

**EXTENDED ANSWERS**

| Typology | Partly confined or unconfined |
|---|---|
| A | Absence of artificial changes of river course in the past (meanders cut-off, channel diversions, etc.). |
| B | Presence of artificial changes of river course in the past for ≤ 10% of the reach length. In the case of anabranching channels, the length of the reach is the sum of all the lengths of single anabranches. |
| C | Presence of artificial changes of river course in the past for > 10% of the reach length. |

## A9: Other bed stabilization structures

**DEFINITION**

This indicator accounts for other crossing structures which, in general, cause bed bottom rigidifying, paving or reinforcement, but without significantly altering the sediment transport. These include **bed sills and ramps** built to reduce the bed incision, often in correspondence with bridges, and **revetments of the channel bed**, both impermeable and permeable. Bed revetments cause strong alteration in channel morphology in terms of the disappearance of sediment and related bed forms (loss of habitats) as well as in terms of an alteration of the vertical continuity with the groundwater (hyporheic zone). These structures are common in steep mountain reaches (to prevent channel incision), but also along urban reaches in partly confined and unconfined channels (to prevent channel sedimentation, e.g. on alluvial fans).

The indicator accounts for bed stabilization structure frequency or percentage and typology (permeable or impermeable) respectively for sills/ramps (also taking into account the reach slope) and revetments.

| Spatial scale | |
|---|---|
| *Longitudinal*: Reach | *Lateral*: Channel |
| **Measurements**: Map layer of interventions, remote sensing, field survey | |

The evaluation is carried out by remote sensing, except for small confined channels, where these structures are not visible (except in the case that very high resolution images are available). When the structures are not visible from remote sensing, the map layer of interventions and/or field surveys is necessary, recording only the number of structures (additional information on typology, characteristics is not required).

**EXTENDED ANSWERS**

| Typology | All typologies |
|---|---|
| A | Absence of other bed stabilization structures (bed sills, ramps) and/or localized revetments (≤ 5% of the reach length) not altering significantly the vertical continuity and bed structure. In the case of anabranching channels, the reach length is the sum of the lengths of anabranches. |
| B | Presence of bed sills and/or ramps with relatively low density, i.e. ≤ 1 every *d* on average along the reach, where *d* = 200 m for steep channels (bed slope *S*>1%) or *d* = 1000 m for bed slope *S*≤1%, and/or limited presence of revetments: bed revetments occupy a length ≤ 25% of the reach with permeable systems and/or ≤ 15% with impermeable systems. |
| C1 | Presence of bed sills/ramps with a density of > 1 every *d* on average in the reach and/or significant presence of revetments: bed revetments occupy a length ≤ 50% of the reach with permeable systems and/or ≤ 33% with impermeable systems. |
| C2 | Widespread presence of revetments: bed revetments occupy a length > 50% of the reach with permeable systems or > 33% with impermeable systems. |
| *Additional scores*<br>*In case of high density of bed revetments, i.e. permeable revetments >80% of the reach length or impermeable revetments >50%, add 6.*<br>*In case of extremely high density of impermeable bed revetments (i.e. >80% of the reach length), add 12.* | |

## Interventions of maintenance and removal

### *A10:* Sediment removal

**DEFINITION**

This indicator aims to provide an evaluation of the existence and relative intensity of sediment removal. Such activity may induce several negative effects, in terms of morphological processes and evolution (bed incision) as well as in terms of ecosystems (Rinaldi et al., 2005).

| Spatial scale | |
|---|---|
| *Longitudinal*: Reach | *Lateral*: Channel |
| **Measurements**: Map layer of interventions, remote sensing, field survey | |

Sediment removal includes either mining activity (excavation of gravel or sand pits for sediment exploitation) and interventions aimed at channel dredging and re-sectioning aimed at reducing flood risk (e.g., channel lowering and widening). The indicator does not account for local sediment removal, such as in the case of maintenance upstream from check dams (these effects are already accounted for by indicator *A4*).

The evaluation is slightly different from **confined** to **partly confined - unconfined channels**. In the former case, the investigated time period is exclusively that of the **last**

**20 years** (coherently with the following two indicators). The difference between the three classes is determined by the extension of any removal activity (absent, localized, widespread in the reach) during this time period. In the case of partly confined - and unconfined channels, two time periods are considered: (a) **recent activity** (last 20 years, as for confined channels); (b) **past activity**, i.e. over the last 100 years. The 1950s is generally the decade of maximum activity in many European countries (Rinaldi et al., 2005) but in other countries, intense sediment dredging may have occurred in the first half of 1900. Concerning recent activity, information can be obtained from public agencies in charge of river management and maintenance and/or from field evidence. Regarding past activity, the indicator intends to provide a gross evaluation limited to the presence or absence of such activity, based on available information, since a quantification of extracted volumes is not possible. To this purpose, **two situations** are considered: (1) absent or negligible past activity of sediment removal; (2) past activity of sediment removal: when there is reliable information that the number of mining sites and the extracted volumes are significant (not negligible). Indirect indicators of intense activity may be the number of mining sites at present or in the past (from aerial photos of the 1950s) in the surroundings of the river channel, intense incision (see *CA3*) that is attributable to mining activity, etc.

**EXTENDED ANSWERS**

| Typology | Confined |
|---|---|
| A | Evidence/reliable information of absent significant sediment removal activity during the last 20 years. |
| B | Evidence/reliable information of significant but localized (only one site) sediment removal activity during the last 20 years. |
| C | Evidence/reliable information of significant and widespread (more sites along the reach) sediment removal activity during the last 20 years. |

| Typology | Partly confined or unconfined |
|---|---|
| A | Absence of significant sediment removal activity either in the past (over the last 100 years) and during about the last 20 years. |
| B1 | Sediment removal activity in the past (last 100 years) but absent during about the last 20 years. |
| B2 | Sediment removal activity during the last 20 years but absent in the past (last 100 years). |
| C | Sediment removal activity in the past (last 100 years) and during the last 20 years. |

## *A11:* Wood removal

**DEFINITION**

Wood removal can periodically be carried out by various public agencies in charge of river management and maintenance, usually in conjunction with cutting vegetation (see next indicator) and/or sediment removal. Typically, only larger sized woody material is removed, while fine woody debris (small trunks, branches) is left in the channel.

Wood removal is justifiable for safety reasons (e.g. creation of wood jams at bridges during flood events), however has a significant impact on the fluvial system (e.g. reduction of hydrodynamic complexity, and therefore morphological and sedimentary diversity, with the disappearance of physical habitats and organic matter for fishes and invertebrates).

| Spatial scale | |
|---|---|
| *Longitudinal*: Reach | *Lateral*: Channel and floodplain |
| **Measurements**: Information by public agencies | |

The indicator is not applied also in the case of areas of **tundra in northern Europe**, where vegetation is naturally absent. For its application, it is necessary to acquire information on **total** or **partial wood removal** (where partial indicates the removal of only some very large wood or localised in specific sites) **during the last 20 years**. This time interval is motivated both by the availability of information from public agencies, and by the natural capability of streams to once again achieve a sufficient quantity of wood from the banks, hillslopes and upstream reaches. In case of a lack of reliable information, the answer is *B*. Cases where *F11* has not been applied are not evaluated. As for indicator *A10*, wood removal in correspondence of check dams is not considered.

**EXTENDED ANSWERS**

| | |
|---|---|
| **Typology** | All typologies |
| **Range of application** | Not evaluated above the tree-line and in streams with natural absence of riparian vegetation, such as in north-european tundra |
| A | Absence of interventions for the removal of large wood (diameter > 10 cm and length > 1 m), at least in the last 20 years, or reliable information of removal of only negligible volumes. |
| B | Reliable information/evidence of partial removal interventions during the last 20 years, that is, the removal of some elements only, often following flood events. Here are also included the cases of permission for removal by private citizens, even without any intervention from public agencies. Some woody material could be cut into elements < 1 m and left within the channel. |
| C | Reliable information/evidence of total removal interventions by public agencies during the last 20 years. Some woody material could be cut into elements < 1 m and left within the channel. |

## *A12:* Vegetation management

**DEFINITION**

**Riparian woody vegetation** in the fluvial corridor (banks, floodplain, recent terraces) and in the channel (mature and pioneer islands) performs several morphological functions, in particular providing wood material (from natural tree death, bank erosion, occasional break, or from hillslope processes in confined channels). Moreover woody vegetation traps sediment and wood material during floods, contributing to the diversity of the river habitat mosaic. **Aquatic emergent vegetation** may also have significant impact on river hydraulics, and consequently on sediment accumulation and erosion (Gurnell et al., 2006).

Similarly to the previous indicator, periodic interventions of vegetation cutting by public agencies are motivated by safety reasons, but they have various impacts on the morphological and biological natural processes related to riparian vegetation. In order to reduce such impacts, public agencies are recently oriented towards selective cutting (involving only the oldest trees) rather than a total removal. The latter approach induces lower impact than the total vegetation cutting on large surfaces, however alters the natural structure of the forest. Vegetation cutting of areas not directly in contact with the channel (but included in the fluvial corridor) has also lower morphological and ecological impacts compared to intervention on channel banks. Note that grazing activity is here assimilated to vegetation cutting, as it prevents vegetation growth. Aquatic emergent vegetation is also frequently removed by cutting and/or dredging for safety reasons.

| Spatial scale | |
|---|---|
| *Longitudinal*: Site/Reach | *Lateral*: channel and portions of floodplain (partly confined - unconfined) adjacent to the banks, or adjacent plain / hillslopes (confined) for woody and shrub vegetation management; channel for aquatic macrophytes |
| **Measurements**: Information from public agencies and field site check (presence of butts) | |

The indicator is also not applied in the case of areas of **tundra in northern Europe**, where vegetation is naturally absent. For its application, the operator must collect information from the **public agencies** responsible for vegetation management, and observe in the field any possible evidence of past cuttings (i.e. presence of butts). The indicator is applied in the case of significant cutting activity (just a few plants cut along the reach are not considered) in the channel (i.e. on islands), within the areas external to the banks (i.e. including the modern floodplain and recent terraces) and on hillslopes. The investigated area corresponds to the width of functional vegetation identified with the indicator *F12*, assumed to be at least equal to $nW$, where $W$ is the channel length, $n$ = 2 for single-thread or anabranching channels, and $n$ = 1 for braided and wandering channels; for confined channels, up to 50 meters on hillslopes and for each bank. For the same reasons as for the previous indicator, the time interval considered includes the **last 20 years** in the case of **riparian vegetation**, whereas the **last 5 years** are considered for **aquatic vegetation**. The indicator is not applied for those reaches where *F12* and *F13* have not been evaluated.

Three cases of management of riparian vegetation are considered: (A) absence or selective cutting within the areas external to the banks; (B) selective cutting along the banks, or total cutting along the banks for ≤50% of the reach length, or total cutting of any distance within the areas external to the banks; (C) total cutting along the banks for >50 % of the reach length.

The evaluation of aquatic vegetation management is considered only in those **low energy channel morphologies** (i.e. low-energy straight, sinuous, meandering and anabranching channels) in which the presence of emergent macrophytes is assessed for the indicator *F13*, and the investigated area corresponds to the channel. In such a case, the following three classes of aquatic vegetation management are considered (similarly to indicator *A11*): (A) absence of cutting and/or dredging; (B) partial cutting and/or dredging; (C) total cutting and/or dredging. The assessments for riparian and aquatic vegetation management are then combined to derive a **combined class** (A, B or C) of the indicator *A12* according to the matrix shown in Table 7.

**Table 7 Definition of the classes for the indicator A12 in the case of low energy channels where the management of emergent aquatic macrophytes is considered.**

| | | **Management of vegetation in the fluvial corridor** | | |
|---|---|---|---|---|
| | | A | B | C |
| **Management of emergent aquatic macrophytes** | A (absence) | **A** | **B** | **C** |
| | B (partial cutting and/or dredging) | **B** | **B** | **C** |
| | C (total cutting and/or dredging) | **B** | **C** | **C** |

**EXTENDED ANSWERS**

| | |
|---|---|
| Typology | All typologies |
| Range of application | Riparian vegetation management: Not evaluated above the tree-line and in streams with natural absence of riparian vegetation, such as in north-european tundra<br>Aquatic vegetation management: evalauted only in low-energy straight, sinuous, meandering and anabranching channels |

| | |
|---|---|
| A | Vegetation not subject to cutting interventions along the banks, or only affected by selective cutting within the areas external to the banks (floodplain for partly confined - unconfined, hillslopes for confined) during the last 20 years.<br>In case of low-energy straight, sinuous, meandering and anabranching channels:<br>Management of vegetation in the fluvial corridor as described above (case A), and absence of cutting and/or dredging of the aquatic emergent macrophytes along the reach during the last 5 years (case A). |
| B | Vegetation subject to interventions of selective cutting along the banks for any distance, or total cutting for a length < 50% of the reach; or total cuttings of any distance within the areas external to the banks (last 20 years). In the case of anabranching channels, the reach length is the sum of the lengths of the anabranches.<br>In case of low-energy straight, sinuous, meandering and anabranching channels:<br>- Management of vegetation in the fluvial corridor as described above (case B), and absence of cutting and/or dredging or reliable information/evidence of partial cutting and/or dredging interventions by public agencies of the aquatic emergent macrophytes during the last 5 years along the reach (case A or B);<br>Or<br>- Management of vegetation in the river corridor as in case A, and reliable information/evidence of partial or total cutting and/or dredging interventions by public agencies of the aquatic emergent macrophytes during the last 5 years along the reach (case B or C). |
| C | Vegetation subject to total cutting along the banks for a distance > 50% of the reach during the last 20 years.<br>In case of low-energy straight, sinuous, meandering and anabranching channels:<br>- Management of vegetation in the fluvial corridor as described above (case C), and any case of management of aquatic vegetation;<br>Or<br>- Management of vegetation in the river corridor as in case B, and reliable information/evidence of total cutting and/or dredging interventions by public agencies of the aquatic emergent macrophytes during the last 5 years along the reach (case C). |

## *Channel Adjustments*

This set of indicators aims to assess channel adjustments (planimetric and vertical changes) which occurred over the previous decades. Only channel adjustments related to human impacts should be quantified, therefore it is crucial to identify the controlling factors of such adjustments. Although channel adjustments are assessed using a simplified method, in most cases it should be possible to obtain a reliable interpretation of their causes by considering the magnitude of these adjustments, as well as the type and frequency of human impacts at the catchment and reach scale. This latter information should be available from the analysis of the previous set of indicators (i.e., indicators of artificial elements). These indicators, however, do not provide a detailed reconstruction of past channel evolution (i.e., channel evolutionary trajectory) but only an overall evaluation of past channel instability. Since these indicators are based on a comparison with a historical condition, only adjustments in channel form are considered, while possible adjustments in bed substrate are not included and are separately assessed by the indicator *F10*.

Although the indicators of channel adjustments are based on an analysis of changes occurring over the last decades, this does not imply that the historical morphology is considered as a 'reference' condition. In fact, these indicators aim to evaluate channel instability as evidence of alteration related to human factors. Since the time interval suitable for this type of evaluation is to the order of approximately 50 – 100 years, should the river morphology have been artificially modified in historical times before this time interval (e.g. during the 18$^{th}$ century), as is often the case in many European fluvial systems, these historical condition should not be considered for the evaluation of channel instability. Even in such cases, the evaluation should be carried out with reference to the same time interval (50 – 100 years). This could probably results in a condition of 'stability' related to the artificial conditions (e.g. fixed planform), however alterations related to the artificial conditions will be taken into account by the indicators of artificial elements and functionality. Note, however, that a fixed channel will not necessarily be stable: although some type of adjustment will be prevented (e.g. widening or meandering in a river with fixed banks), other types of changes are still possible (e.g. narrowing, aggradation).

### *CA1:* Adjustments in channel pattern

**DEFINITION**

This indicator evaluates the occurrence and intensity of adjustments in channel morphological configuration, i.e. the change in channel pattern (sinuous, meandering, braided, etc.). A change in channel pattern during the last decades is generally a symptom of an alteration of some of the processes controlling channel morphology (in particular of the driving variables, i.e. flow regime and sediment transport). Significant changes in channel pattern cause an alteration of river habitats and ecosystems related to the different channel morphologies. Channel pattern changes due to direct artificial interventions are also considered by this indicator (e.g. a braided channel which moves toward a single-thread channel because of channelization; or a meandering channel becoming sinuous because of artificial meander cutting). Differently, the cases when a natural cause of the channel adjustments is clearly recognized (e.g. a landslide dam or a volcanic eruption which determines the channel pattern change) are not evaluated as an alteration. Furthermore, should the reach have recently been subject to a morphological river restoration (e.g. removal of artificial constraints or "morphological reconstruction"), the indicator *CA1* is not applied (as well as the indicator *CA2*). In fact, channel pattern change from a former altered situation is not considered as a negative channel adjustment (note that possible positive effects of restoration activities are already taken into account through the improved functionality and the reduction of artificial elements).

The assessment of the first two indicators *CA1* and *CA2* is based on the observation and analysis of **aerial photos**, comparing the current conditions with a representative, historical situation. Since aerial photos suitable for this type of assessment are variable across European countries, **a range between about the 1930s and 1960s** is suggested. Aerial photos suitable for these indicators should possibly have a homogeneous (scale wise) national cover, with sufficient resolution for this type of assessment. For example, in Italy a homogeneous national cover of aerial photos dated 1954-55 (IGM GAI) is used (scale of about 1:33.000). The choice of this time interval is also motivated by the fact that for most Italian rivers, the most significant part of the planimetric adjustments over the last 100 years generally occurred from about the 1950s to the early 1990s (Rinaldi and Simon, 1998; Surian and Rinaldi, 2003; Surian et al., 2009), in coincidence with the economical development after World War II. A similar reason can be considered as extendable to many other European countries (e.g., Liébault and Piégay, 2002; Wyżga, 2008).

| Spatial scale | |
|---|---|
| *Longitudinal*: Reach | *Lateral*: Entire floodplain (including recent terraces) |
| **Measurements**: Remote sensing / GIS analysis | |

The indicator *CA1* is applied to **all river typologies**. However, the potential of aerial imagery analysis is limited by **stream size**, vegetation cover and the resolution of the imagery that is available. Where streams are too small to be observed and quantified by aerial photos, the indicator *CA1* (as well as *CA2*) is not applied. A fixed threshold in stream size is avoided, but the operator should evaluate whether the **resolution of available aerial photos** is sufficient to carry out the assessment.

The indicator is applied both to confined and partly confined - unconfined, although some differences in the classes exist. In the case of **confined channels**, only two classes are distinguished (*A* and *B*) because a significant change in channel pattern (e.g. from braided to single-thread) and/or in channel width (channel narrowing: see *CA2*) consequently leads to a transformation into a partly confined or unconfined channel. In the cases of **partly confined - unconfined channels**, the assignation to class *B* or *C* depends on whether the change has occurred between similar morphologies (e.g. from meandering to sinuous) or between markedly different morphologies (e.g. from braided to sinuous), as defined in Table 8.

**Table 8 Classes for the different possible adjustments in channel morphologies. Morphologies: ST = straight, S = sinuous, M = Meandering, W = Wandering, B = Braided, A = Anabranching; ⇔ = change in both directions. Class: B = change to a similar morphology; C = change to a markedly different morphology.**

| Morphology | Class | Morphology | Class |
|---|---|---|---|
| *ST ⇔ S* | *B* | *S ⇔ A* | *B* |
| *ST ⇔ M* | *C* | *M ⇔ W* | *C* |
| *ST ⇔ W* | *C* | *M ⇔ B* | *C* |
| *ST ⇔ B* | *C* | *M ⇔ A* | *B* |
| *ST ⇔ A* | *C* | *W ⇔ B* | *B* |
| *S ⇔ M* | *B* | *W ⇔ A* | *C* |
| *S ⇔ W* | *C* | *B ⇔ A* | *C* |
| *S ⇔ B* | *C* | | |

In many cases, a qualitative observation of the channel pattern in the two aerial photos is sufficient to evaluate whether a significant channel pattern adjustment occurred (e.g. from braided to single-thread). In other cases, measurement of some indices for defining channel morphology (sinuosity index, braiding index, etc.) may be necessary. Measurement of channel pattern indices requires a GIS analysis, including the georectification of the different images.

**EXTENDED ANSWERS**

| | | |
|---|---|---|
| Typology | | Confined |
| Range of application | | Not evaluated in the case of too small streams where resolution of available aerial photos is insufficient to allow for the assessment. It does not apply to the case of restored channels which were artificially fixed during the 1930s - 1960s. |
| A | Absence of changes of channel pattern from 1930s-1960s. | |
| B | Change of channel pattern from 1930s-1960s. | |

| | | |
|---|---|---|
| Typology | | Partly confined or unconfined |
| Range of application | | Not evaluated in the case of too small streams where resolution of available aerial photos is insufficient to allow for the assessment. It does not apply to the case of restored channels which were artificially fixed during the 1930s - 1960s. |
| A | Absence of changes of channel pattern from 1930s-1960s. | |
| B | Change to a similar channel pattern from 1930s-1960s (Table 8). | |
| C | Change to a different channel pattern from 1930s-1960s (Table 8). | |

### *CA2:* Adjustments in channel width

**DEFINITION**

This indicator evaluates the occurrence and amount of changes in channel width from a period included in the interval 1930s - 1960s to present day. River channels can considerably change in terms of channel width, even maintaining their general channel pattern morphology, because of direct artificial interventions (e.g. artificial narrowing, groynes, etc.), but also because of an alteration of the driving variables controlling channel morphology (channel-forming and sediment discharges). The existence of significant adjustments in channel width variations in a temporal interval of 50-80 years is considered here as evidence of morphological instability, and may have caused strong habitat and ecosystem modifications. The indicator also includes those cases where change in channel width was caused by direct artificial interventions (e.g. narrowing of a braided channel following channelization). As for *CA1*, when a natural cause is clearly recognized (e.g. a landslide dam or a volcanic eruption which determines the channel pattern change), the channel adjustment is not evaluated as an alteration. Furthermore, in the case of a river which was artificially fixed in the 1930s – 1960s and was recently subject to a morphological river restoration (e.g. removal of artificial constraints or "morphological reconstruction"), this indicator is not applied.

| Spatial scale | |
|---|---|
| *Longitudinal*: Reach | *Lateral*: Entire floodplain (including recent terraces) |
| **measurements**: Remote sensing / GIS analysis | |

As for the previous indicator, this indicator is applied to **all river typologies**, excluding the case of streams which are too small to be observed and quantified by aerial photos. A fixed threshold in stream size is avoided, but the operator should evaluate whether the **resolution of available aerial photos** is sufficient to carry out the assessment.

The indicator is applied both to confined and partly confined - unconfined, although some differences in the classes exist. In **confined channels**, only two classes (*A* and *B*) are defined (in fact significant channel narrowing would determine a change to an unconfined channel). Measurement of changes in channel width requires a GIS analysis, including the georectification of the different images, the digitizing of channel margins and the measurement of the channel width.

**EXTENDED ANSWERS**

| Typology | Confined |
|---|---|
| Range of application | Not evaluated in the case of too small streams where resolution of available aerial photos is insufficient to allow for the assessment. It does not apply to the case of restored channels which were artificially fixed during the 1930s - 1960s. |
| A | Absent or limited changes in channel width (≤ 15%) from 1930s-1960s. |
| B | Changes in channel width > 15% from 1930s-1960s. |

| Typology | Partly confined or unconfined |
|---|---|
| Range of application | Not evaluated in the case of too small streams where resolution of available aerial photos is insufficient to allow for the assessment. It does not apply to the case of restored channels which were artificially fixed during the 1930s - 1960s. |
| A | Absent or limited changes in channel width (≤ 15%) from 1930s-1960s. |
| B | Moderate changes in channel width (15÷35%) from 1930s-1960s. |
| C | Intense changes in channel width (> 35%) from 1930s-1960s. |

### *CA3:* Bed-level adjustments

**DEFINITION**

This indicator accounts for the occurrence and amount of bed-level adjustments (incision or aggradation). Bed-level changes in alluvial channels may be caused by changes of some factor controlling channel morphology, particularly by alterations of flow and/or sediment discharge. When bed-level adjustments occur in a relatively short time scale, they are generally related to some human impact (e.g. land use changes at the catchment scale, dams, sediment mining, etc.). They are considered among the most relevant physical alterations affecting a number of processes (e.g. lateral connection with floodplain, alteration of in-channel habitats, etc.).

| Spatial scale | |
|---|---|
| *Longitudinal*: Reach | *Lateral*: Channel |
| **Measurements**: Data from cross-sections / longitudinal profiles, field survey | |

This indicator is based on **existing data** (e.g. longitudinal profiles or cross sections), information from existing literature, and **field evidence** of bed-level changes. Differently from planimetric changes, in this case bed-level changes are referred to a wider temporal scale, i.e. about the last 100 years. This is related to the fact that, according to existing research (e.g., Surian and Rinaldi, 2003; Surian et al., 2009; Liébault and Piégay, 2002; Liébault et al., 2012), one or more phases of incision followed a period of predominant aggradation or equilibrium occurring until about the end of the 19$^{th}$ century. This simplification allows a better utilization of field evidence, consisting of an evaluation of the differences in elevation between a modern floodplain and recent terraces, the latter coinciding with the historical floodplain before the incision (Rinaldi, 2003; Liébault et al., 2012). These observations can also be supported by the analysis of aerial photos, which can allow the collection of detailed chronological information on the surfaces where differences in elevation are measured in the field.

On the basis of available data and/or field evidence and survey, an evaluation of the range of bed-level changes (rather than a precise value) is obtained. In the cases of an **absolute lack of data**, field evidence or other sources of information, this indicator is omitted and is not included in the final score.

Similarly to *CA1* and *CA2*, this indicator applies both to **confined and partly confined - unconfined**, but with some differences. In the case of partly confined - unconfined channels, a class *C2* is defined to account for cases of dramatic changes in bed elevation (> 6 m), which are very unusual in the case of confined channels.

**EXTENDED ANSWERS**

| | |
|---|---|
| Typology | Confined |
| Range of application | Not evaluated in the case of absolute lack of data and field evidence |
| A | Negligible bed-level changes (≤ 0.5 m). |
| B | Limited or moderate bed-level changes (0.5÷3 m). |
| C | Intense bed-level changes (> 3 m). |

| | |
|---|---|
| Typology | Partly confined or unconfined |
| Range of application | Not evaluated in the case of absolute lack of data and field evidence |
| A | Negligible bed-level changes (≤ 0.5 m): bed elevation unchanged due to altimetric stability or to recovery by aggradation of a previous phase of incision (e.g. due to a weir). |
| B | Limited or moderate bed-level changes (≤ 3 m). Incised channel: differences in elevation exist between new floodplain (if existing) and recent terraces, but in many cases not evident. Aggraded channel: bed-elevation higher than floodplain elevation. |
| C1 | Intense bed-level changes (3÷6 m). Highly incised channel: very evident differences in elevation between new floodplain (if existing) and recent terraces, with the presence of evidence in several forms, including high and unstable banks, destabilization of transversal structures, exposed bridge piers, etc. Highly aggraded channel: marked differences in elevation between channel bed (much higher) and floodplain. |
| C2 | Very intense bed-level changes (> 6 m). Exceptionally incised channel (e.g. following intense mining activity in the past). Usually, as well as the aforementioned evidence, data or reliable information about such an important incision will exist. Exceptionally aggraded channel. |

## *Scores*

For each indicator, the **partial score** relative to classes *A*, *B* or *C* must be circled in the apposite column on the right (first column on the right side of the answers). In the following column, the **progressive score** is reported, so that the total deviation is immediately available at the end of the compilation of the evaluation form. In the last column on the right (inside the dotted lines), operator should express a **degree of confidence** in the answer, considering three possible cases: (1) *High*, (2) *Medium*, (3) *Low*. This can be indicated between class *A* and *B*, or between *B* and *C*. A simplified estimation of the overall uncertainty degree associated with the final evaluation can be obtained that is the range of variation of the final score. An example of the procedure can be visualized in the **compiled evaluation form** (see later).

For some indicators, two **additional scores** ("extra-penalties" of 6 and 12, respectively) can be added in case of extremely dense, dominant presence of artificial elements along the reach. This rule concern the indicators A4, A6, A7, and A9, and was included to adequately rank river reaches with only one or just a few types of artificial elements but at very large extensions and/or density, heavily affecting the overall morphological conditions.

On the bottom of the evaluation form, the Morphological Alteration Index and the Morphological Quality Index are calculated.

The **Morphological Alteration Index** (***MAI***) is calculated as:

$$MAI = S_{tot} / S_{max}$$

where $S_{max}$ is the maximum possible deviation for the given stream typology (it corresponds to the sum of the class C scores for all the questions applicable to the study case).

The **Morphological Quality Index** (***MQI***) is expressed as:

$$MQI = 1 - MAI$$

## *Sub-indices*

Given the structure divided into various aspects and categories, it is possible to calculate a series of sub-indices, that is, to sub-divide the two main indices *MAI* and *MQI* into their components. This can be useful for identifying the negative and positive points of a reach.

The **sub-indices** of **functionality**, **artificiality,** and **channel adjustments** (or "vertical sub-indices") can be obtained as follows:

1. <u>**FUNCTIONALITY**</u>

$\boldsymbol{MAI_F} = S_F\,tot/Smax$

$\boldsymbol{MQI_F} = (S_F\,max/Smax) - MAI_F = (S_F\,max - S_F\,tot) / Smax$

where

$\boldsymbol{S_F\,tot} = F1 +\ldots+ F13$ *(sum of scores of applied F indicators);*

$\boldsymbol{Max(S_F\,tot)} = Max(F1) +\ldots+ Max(F13)$ *(sum of maximum scores of all F indicators);*

$\boldsymbol{Max(S_A\,tot)} = Max(A1) +\ldots+ Max(A12)$ *(sum of maximum scores of all A indicators);*

$\boldsymbol{Max(S_{CA}\,tot)} = Max(CA1) +\ldots+ Max(CA3)$ *(sum of maximum scores of all CA indicators);*

$\boldsymbol{Max(Stot)} = Max(S_F\,tot) + Max(S_A\,tot) + Max(S_{CA}\,tot)$ *(sum of maximum scores of all indicators);*

$\boldsymbol{Sna(_F)}$ = *sum of maximum scores of not applied F indicators;*

$\boldsymbol{Sna}$ = *sum of maximum scores of not applied F, A, CA indicator;*

$\boldsymbol{S_F}$ **max** = $Max(S_F\,tot) - Sna(_F)$;

**Smax** = $Max(Stot) - Sna$.

2. **ARTIFICIALITY**

$\boldsymbol{MAI_A}$ = $S_A\,tot/Smax$

$\boldsymbol{MQI_A}$ = $(S_A\,max/Smax) - MAI_A = (S_A\,max - S_A\,tot) / Smax$

where:

$\boldsymbol{S_A}$**tot** = $A1 + \ldots + A12$ (sum of scores of applied A indicators);

**Max(**$\boldsymbol{S_F}$ **tot)** = $Max(F1) + \ldots + Max(F13)$ (sum of maximum scores of all F indicators);

**Max(**$\boldsymbol{S_A}$ **tot)** = $Max(A1) + \ldots + Max(A12)$ (sum of maximum scores of all A indicators);

**Max(**$\boldsymbol{S_{CA}}$ **tot)** = $Max(CA1) + \ldots + Max(CA3)$ (sum of maximum scores of all CA indicators);

**Max(Stot)** = $Max(S_F\ tot) + Max(S_A\ tot) + Max(S_{CA}\ tot)$ (sum of maximum scores of all indicators);

**Sna(**$_A$**)** = sum of maximum scores of not applied A indicators;

**Sna** = sum of maximum scores of not applied F, A, CA indicator;

$\boldsymbol{S_A}$ **max**= $Max(S_A\,tot) - Sna(_A)$;

**Smax** = $Max(Stot) - Sna$.

3. **CHANNEL ADJUSTMENTS**

$\boldsymbol{MAI_{CA}}$ = $S_{CA}\,tot/Smax$

$\boldsymbol{MQI_{CA}}$= $(S_{CA}max/Smax) - MAI_{CA} = (S_{CA}\,max - S_{CA}\,tot) / Smax$

where:

$\boldsymbol{S_{CA}}$ **tot** = $CA1 + \ldots + CA3$ (sum of scores of applied CA indicators);

**Max(**$\boldsymbol{S_F}$ **tot)** = $Max(F1) + \ldots + Max(F13)$ (sum of maximum scores of all F indicators);

**Max(**$\boldsymbol{S_A}$ **tot)** = $Max(A1) + \ldots + Max(A12)$ (sum of maximum scores of all A indicators);

**Max(**$\boldsymbol{S_{CA}}$ **tot)** = $Max(CA1) + \ldots + Max(CA3)$ (sum of maximum scores of all CA indicators);

**Max(Stot)** = $Max(S_F\ tot) + Max(S_A\ tot) + Max(S_{CA}\ tot)$ (sum of maximum scores of all indicators);

**Sna(**$_{CA}$**)** = sum of maximum scores of not applied CA indicators;

**Sna** = sum of maximum scores of not applied F, A, CA indicator;

$\boldsymbol{S_{CA}}$ **max**= $Max(S_{CA}\,tot) - Sna(_{CA})$;

**Smax** = $Max(Stot) - Sna$.

To make the analysis more effective, the sub-indices can be related to the maximum value that they can reach for a given category (functionality, artificiality, channel changes). For this purpose, the overall value of *MAI* and *MQI* is divided in the part relative to each category as follows:

1. **FUNCTIONALITY**

$MAI_F\,max = MQI_F\,max = S_F\,max/Smax$

2. **ARTIFICIALITY**

$MAI_A\,max = MQI_A\,max = S_A\,max/Smax$

3. **CHANNEL ADJUSTMENTS**

$MAI_{CA}\,max = MQI_{CA}\,max = S_{CA}\,max/Smax$

Note that, in case of additional scores for the indicators *A4*, *A6*, *A7*, *A9* such that $Stot > Smax$, the sum of the three sub-indices $MAI_F$+$MAI_A$+$MAI_{CA}$ is >1.

Similarly, **continuity**, **morphology** and **vegetation sub-indices** (or "horizontal sub-indices") can be obtained. For this purpose, some element of artificiality needs to be shared in more categories: in such cases the score assigned to a given indicator is simply divided by the number of categories. The sub-indices are defined as follows.

## 1. CONTINUITY

$MAI_C=MAI_{CL}+MAI_{CLA}$

$MQI_C=MQI_{CL}+MQI_{CLA}$

where:

*C is for continuity, CL is for longitudinal continuity and CLA is for lateral continuity*

### 1.1. LONGITUDINAL CONTINUITY

$MAI_{CL} = (F1+A1+A2+A3+A4/2+A5)/Smax$
$MQI_{CL}=(S_{CL}\,max/Smax) – MAI_{CL}$

where:

$\mathbf{S_{CL}\,max}= Max(S_{CL}\,tot) – Sna(_{CL})$;
$\mathbf{Max(S_{CL}\,tot)} = Max(F1)+Max(A1)+Max(A2)+Max(A3)+Max(A4/2)+ Max(A5)$
*(sum of maximum scores of all CL indicators);*

$\mathbf{Sna(_{CL})}$ = *sum of maximum scores of not applied CL indicators.*

### 1.2. LATERAL CONTINUITY

$MAI_{CLA} = (F2+F3+F4+F5+A6/2+A7)/Smax$
$MQI_{CLA}=(S_{CLA}\,max/Smax) – MAI_{CLA}$

where:

$\mathbf{S_{CLA}\,max}= Max(S_{CLA}\,tot) – Sna(_{CLA})$;
$\mathbf{Max(S_{CLA}\,tot)} = Max(F2)+Max(F3)+Max(F4)+Max(F5)+Max(A6/2)+ Max(A7)$
*(sum of maximum scores of all CLA indicators);*

$\mathbf{Sna(_{CLA})}$ = *sum of maximum scores of not applied CLA indicators.*

## 2. MORPHOLOGY

$MAI_M=MAI_{CM}+MAI_{CS}+MAI_S$

$MQI_M=MQI_{CM}+MQI_{CS}+MQI_S$

where:

*M is for morphology, CM is for morphological pattern, CS is for cross-section configuration and S is for substrate.*

### 2.1. MORPHOLOGICAL PATTERN

$MAI_{CM} = (F6+F7+F8+A6/2+A8+CA1)/Smax$
$MQI_{CM}=(S_{CM}\,max/Smax) – MAI_{CM}$

where:

$\mathbf{S_{CM}\,max}= Max(S_{CM}\,tot) – Sna(_{CM})$;
$\mathbf{Max(S_{CM}\,tot)} = Max(F6)+Max(F7)+Max(F8)+ Max(A6/2)+ Max(A8)+ Max(CA1)$
*(sum of maximum scores of all CM indicators);*
$\mathbf{Sna(_{CM})}$ = *sum of maximum scores of not applied CM indicators.*

### 2.2. CROSS-SECTION CONFIGURATION

$MAI_{CS} = (F9+A4/2+A9/2+A10/2+CA2+CA3)/Smax$
$MQI_{CS}=(S_{CS}\,max/Smax) – MAI_{CS}$

where:

$\mathbf{S_{CS}\,max}= Max(S_{CS}\,tot) – Sna(_{CS})$;
$\mathbf{Max(S_{CS}tot)}=Max(F9)+Max(A4/2)+Max(A9/2)+Max(A10/2)+Max(CA2)+Max(CA3)$
*(sum of maximum scores of all CS indicators);*
$\mathbf{Sna(_{CS})}$ = *sum of maximum scores of not applied CS indicators.*

### 2.3. SUBSTRATE

$MAI_S = (F10+F11+A9/2+A10/2+A11)/Smax$
$MQI_S=(S_S\,max/Smax) – MAI_S$

where:

$\mathbf{S_S\,max}= Max(S_S\,tot) – Sna(_S)$;
$\mathbf{Max(S_Stot)}=Max(F10)+Max(F11)+Max(A9/2)+Max(A10/2)+Max(A11)$
*(sum of maximum scores of all S indicators);*
$\mathbf{Sna(_S)}$ = *sum of maximum scores of not applied S indicators.*

## 3. VEGETATION

$MAI_{VE}$ = (F12+F13+A12)/Smax

$MQI_{VE}$=($S_{VE}$ max/Smax) – $MAI_{VE}$

where:

*VE is for vegetation;*

***$S_{VE}$* max**= Max($S_{VE}$ tot) **–** Sna($_{VE}$);

**Max($S_{VE}$ tot)** = *Max(F12)+Max(F13)+ Max(A12) (sum of maximum scores of all VE indicators);*

**Sna($_{VE}$)** = *sum of maximum scores of not applied VE indicators.*

As before, the sub-indices can be related to the maximum value that they can reach for a given category, by dividing overall value of *MAI* and *MQI* in the part relative to each category as follows:

1. **CONTINUITY**

$MAI_C$ max = $MQI_C$ max = $S_C$ max/Smax

where:
**$S_C$ max**= Max($S_C$ tot) **–** Sna($_C$) = $S_{CL}$ max + $S_{CLA}$ max;
**Max($S_C$ tot)** = Max($S_{CL}$ tot) + Max($S_{CLA}$ tot)
*(sum of maximum scores of all C indicators, or sum of maximum scores of all CL and CLA indicators);*
**Sna($_C$)** = Sna($_{CL}$) + Sna($_{CLA}$)
*(sum of maximum scores of not applied C indicators, or sum of maximum scores of not applied CL and CLA indicators).*

2. **MORPHOLOGY**

$MAI_M$ max = $MQI_M$ max = $S_M$ max/Smax

where:
**$S_M$ max**= Max($S_M$ tot) **–** Sna($_M$) = $S_{CM}$ max + $S_{CS}$ max + $S_S$ max;
**Max($S_M$ tot)** = Max($S_{CM}$ tot) + Max($S_{CS}$ tot) + Max($S_S$ tot)
*(sum of maximum scores of all M indicators, or sum of maximum scores of all CM, CS and S indicators);*

**Sna($_M$)** = Sna($_{CM}$) + Sna($_{CS}$) + Sna($_S$)

*(sum of maximum scores of not applied M indicators, or sum of maximum scores of not applied CM, CS and S indicators).*

3. **VEGETATION**

$MAI_{VE}$ max = $MQI_{VE}$ max = $S_{VE}$ max/Smax

**EXAMPLE OF COMPILED EVALUATION FORM**

An example of a compiled evaluation form is reported as follows. This example is useful in understanding how to compile the forms and in accounting for the confidence degree in the calculation of the range of variability of *MQI*.

# Morphological Quality Index (MQI)

## EVALUATION FORMS FOR PARTLY CONFINED AND UNCONFINED CHANNELS

*Version 1 - October 2015*

### GENERALITY

Date 01 / 01 / 20 14 Operators J. Smith
Catchment Reform Stream/river Reform River
Upstream limit confluence Reform branch Downstream limit nearby Willington
Segment code 4 Reach Code 4-3 Reach length (m) 2.4 km

### DELINEATION OF SPATIAL UNITS

**1. Physiographic setting**

Physiographic context P *M*=Mountains, *H*=Hills, *P*=Plain Landscape unit High plain

**2. Confinement**

Confinement degree (%) 10- 90 >90, 10-90, ≤10
Confinement index >n 1-1.5, 1.5-*n*, >*n* *(n=5 single-thread channels; n=2 multi-thread or wandering channels)*
Confinement class SC *PC*=Partly confined, *U*=Unconfined

**3. Channel morphology**

Aerial photo or satellite image Aerial Flight Reform Region 2007 (name, year)
Sinuosity index 1.2 1-1.05, 1.05-1.5, >1.5
Braiding index 1.3 1-1.5, >1.5 Anabranching index 1 1-1.5, >1.5
Typology W *ST*=Straight*, S*=Sinuous*, M*=Meandering*, W*= Wandering, *B*= Braided, *A*= Anabranching
Bed configuration ____ *BR*=bedrock, *C*=Cascade, *SP*=Step Pool, *PB*=Plane bed, *RP*=Riffle Pool, *DR*=Dune ripple
(only for single-thread channels) *A*= Artificial, *NC*= not classified (high depth or strong alteration)
Mean bed slope, $S$ 0.0035 Mean channel width, $W$ (m) 42
Bed sediment (dominant) G-C *C*=Clay, *Si*=Silt, *Sa*=Sand, *G*=Gravel, *C*=Cobbles, *B*=Boulders

**4. Other elements for reach delineation**

Upstream Tributary Downstream ____
change in geomorphic units, bed slope discontinuity, tributary, dam, artificial elements, change in confinement and/or size of the floodplain, changes in grain size, other (specify) ____

**Additional available data / information**

Drainage area (at the downstream limit) (km$^2$) 760
Sediment size, $D_{50}$ (mm) 35 Unit Ba(SU) *Be*=Bed, *Ba*=Bar (*SU*=surface layer, *SUB*=sublayer)
Discharges NA *M*=measured, E=estimated, *NA*=not available
Gauging station (if *M*) ____ Mean annual discharge (m$^3$/s) ____ $Q_{1.5}$ or $Q_2$ (m$^3$/s) ____
Maximum discharges (indicate year and Q when known) Intense flood in 2004

### GEOMORPHOLOGICAL FUNCTIONALITY

**Continuity**

| | | part. | prog. | conf. |
|---|---|---|---|---|
| **F1** | **Longitudinal continuity in sediment and wood flux** | | | |
| A | Absence of alteration in the continuity of sediment and wood | 0 | | |
| B | Slight alteration (obstacles to the flux but with no interception) | 3 | | |
| C | Strong alteration (discontinuity of channel forms and interception of sediment and wood) | 5 | 5 | |

There is a large check dam intercepting most of the bedload and creating a discontinuity of channel forms (disappearence of bars downstream)

| | | part. | prog. | conf. |
|---|---|---|---|---|
| **F2** | **Presence of a modern floodplain** | | | |
| A | Presence of a continuous (>66% of the reach) and wide modern floodplain | 0 | | |
| B1 | Presence of a discontinuous (10÷66%) but wide modern floodplain or >66% but narrow | 2 | | |
| B2 | Presence of a discontinuous (10÷66%) and narrow modern floodplain | 3 | | M +2 |
| C | Absence of a modern floodplain or negligible presence (≤10% of any width) | 5 | 8 | |

*Not evaluated in the case of mountain streams along steep (>3%) alluvial fans*

There is some uncertainty for part of the reach whether it is a modern floodplain or a low terrace

*part.*: partial scores (to circle) *prog.*: progressive scores *confidence level between A and B*
*conf.*confidence level in the answer, with *M*=Medium, *L*=Low *(High is omitted)* *confidence level between B and C*

1 of 5

## Morphological Quality Index (MQI)

| F4 | Processes of bank retreat | | |
|---|---|---|---|
| A | Bank erosion occurs for >10% and is distributed along >33% of the reach | 0 | |
| B | Bank erosion occurs for ≤10%, or for >10% but is concentrated along ≤33% of the reach or significant presence (>25%) of eroding banks by mass failures | 2 | |
| C | Complete absence (≤2%) or widespread presence (>50%) of eroding banks by mass failures | 3 | 8 |

*Not evaluated in the case of low energy straight, sinuous and anabranching channels and groundwater-fed streams*

| F5 | Presence of a potentially erodible corridor | | |
|---|---|---|---|
| A | Presence of a wide potentially erodible corridor (EC) for a length >66% of the reach | 0 | |
| B | Presence of a narrow potentially EC for >66%, or wide but for 33-66% of the reach | 2 | |
| C | Presence of a potentially EC of any width but for ≤33% of the reach | 3 | 10 |

**Morphology**

*Morphological pattern*

| F7 | Planform pattern | | |
|---|---|---|---|
| A | Absence (<5%) of alteration of the natural heterogeneity of geomorphic units and channel width | 0 | |
| B | Alterations for a limited portion of the reach (≤33%) | 3 | |
| C | Consistent alterations for a significant portion of the reach (>33%) | 5 | 13 |

| F8 | Presence of typical fluvial landforms in the floodplain | | |
|---|---|---|---|
| A | Presence of floodplain landforms (oxbow lakes, secondary channels, etc.) | 0 | |
| B | Presence of traces of landforms (abandoned during the last decades) but with possible reactivation | 2 | |
| C | Complete absence of floodplain landforms | 3 | No |

*Evaluated only in the case of meandering rivers (now or in the past) excluding groundwater-fed streams*

*Cross-section configuration*

| F9 | Variability of the cross-section | | |
|---|---|---|---|
| A | Absence (≤5%) of alteration of the cross-section natural heterogeneity (channel depth) | 0 | |
| B | Presence of alteration (cross-section homogeneity) for a limited portion of the reach (≤33%) | 3 | |
| C | Presence of alteration (cross-section homogeneity) for a significant portion of the reach (>33%) | 5 | 16 |

*Not evaluated in the case of low energy straight, sinuous, meandering or anabranching channels with natural absence of bars (lowland rivers, low gradients and/or low bedload) and groundwater-fed streams (natural cross-section homogeneity)*

*Bed structure and substrate*

| F10 | Structure of the channel bed | | |
|---|---|---|---|
| A | Natural heterogeneity of bed sediments and no significant armouring and/or clogging | 0 | |
| B | Evident armouring or clogging for ≤50% of the reach | 2 | |
| C1 | Evident armouring or clogging for >50% of the reach or occasional substrate outcrops (≤33% of the reach) related to recent bed-incision of the alluvial substrate | 5 | |
| C2 | Widespread alteration of substrate due to bed revetment or substrate outcrops (>33% of the reach) | 6 | 21 |

*Not evaluated for sand-bed rivers, and for deep rivers when it is not possible to observe the channel bed*

| F11 | Presence of in-channel large wood | | |
|---|---|---|---|
| A | Significant presence of large wood along the whole reach (or "wood transport" reach) | 0 | |
| B | Negligible presence of large wood for ≤50% of the reach | 2 | |
| C | Negligible presence of large wood for >50% of the reach | 3 | 21 |

*Not evaluated above the tree-line and in streams with natural absence of riparian vegetation (e.g. north-European tundra)*

2 of 5

# Morphological Quality Index (MQI)

## Vegetation in the fluvial corridor

| F12 | Width of functional vegetation | | |
|---|---|---|---|
| A | High width of functional vegetation | 0 | |
| B | Medium width of functional vegetation | 2 | |
| C | Low width of functional vegetation | 3 | 23 |

*Not evaluated above the tree-line and in streams with natural absence of riparian vegetation (e.g. north-European tundra)*

| F13 | Linear extension of functional vegetation and presence of emergent aquatic macrophytes | | |
|---|---|---|---|
| A | Riparian vegetation >90% of maximum length, or riparian vegetation>33% and significant presence presence of emergent aquatic vegetation (low-energy channels) | 0 | |
| B | Riparian vegetation 33÷90%, or riparian vegetation >90% but very limited presence of aquatic vegetation, or riparian vegetation ≤33% but significant presence of aquatic vegetation | 3 | |
| C | Riparian vegetation ≤33%, or <90% but very limited presence of aquatic vegetation | 5 | 26 |

*Riparian vegetation not evaluated above the tree-line and in streams with natural absence (e.g. north-European tundra)*
*Aquatic vegetation evaluated only in low-energy straight, sinuous, meandering or anabranching channels*

## ARTIFICIALITY

### Upstream alteration of longitudinal continuity

| A1 | Upstream alteration of flows | part. | prog. | conf. |
|---|---|---|---|---|
| A | No significant alteration (≤10%) of channel-forming discharges and with return interval>10 years | 0 | | |
| B | Significant alteration (>10%) of discharges with return interval>10 years or release of increased low flows downstream dams during dry seasons | 3 | | |
| C | Significant alteration (>10%) of channel-forming discharges | 6 | 29 | |

| A2 | Upstream alteration of sediment discharges | | |
|---|---|---|---|
| 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 | |
| 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 >33% *plain/hills* or >66% *mountains*) | 3 | |
| B2 | Dams (drainage 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 | 35 |

### Alteration of longitudinal continuity in the reach

| A3 | Alteration of flows in the reach | | |
|---|---|---|---|
| A | No significant alteration (≤10%) of channel-forming discharges and with return interval>10 years | 0 | |
| B | Significant alteration (>10%) of discharges with return interval>10 years | 3 | |
| C | Significant alteration (>10%) of channel-forming discharges | 6 | 35 |

| A4 | Alteration of sediment discharge in the reach | | |
|---|---|---|---|
| A | Absence of structures for the interception of sediment fluxes (dams, check dams, abstraction weirs) | 0 | |
| B | *Channels with S≤1%:* consolidation check dams and/or abstraction weirs ≤1 every 1000 m<br>*Steep channels (S>1%):* consolidation check dams ≤1 every 200 m and/or open check dams | 4 | |
| C | *Channels with S≤1%:* consolidation check dams and/or abstraction weirs >1 every 1000 m<br>*Steep channels (S>1%):* consolidation check dams >1 every 200 m and/or retention check dams or presence of a dam or artificial reservoir at the downstream boundary (*any physiographic units*) | 6 | 39 |

*In case of density of interception structures, including bed sills and ramps (see A9), is >1 every d1, add* 6
*In case of density of interception structures, including bed sills and ramps (see A9), is >1 every d2, add* 12
*where d1=150 m and d2=100 m in steep channels, or d1=750 m and d2=500 m in channels with S≤1%*

## Morphological Quality Index (MQI)

| A5 | Crossing structures | | |
|---|---|---|---|
| A | Absence of crossing structures (bridges, fords culverts) | 0 | |
| B | Presence of some crossing structure (≤1 every 1000 m in average in the reach) | 2 | |
| C | Presence of many crossing structure (>1 every 1000 m in average in the reach) | 3 | 41 |

### Alteration of lateral continuity

| A6 | Bank protections | | |
|---|---|---|---|
| A | Absence or localized presence of bank protections (≤5% total length of the banks) | 0 | |
| B | Presence of protections for ≤33% total length of the banks (sum of both banks) | 3 | |
| C | Presence of protections for >33% total length of the banks (sum of both banks) | 6 | 41 |

*In case of high density of bank protection (>50%) add* 6
*In case of extremely high density of bank protection (>80%) add* 12

| A7 | Artificial levees | | |
|---|---|---|---|
| A | Absent or set-back levees, or presence of close and/or bank-edge levees ≤10% bank length | 0 | |
| B | Bank-edge levees ≤50%, or ≤33% in case of total of close and/or bank edge>90% | 3 | |
| C | Bank-edge levees >50%, or >33% in case of total of close and/or bank edge>90% | 6 | 41 |

*In case of extremely high density of bank-edge levees (>66%) add* 6
*In case of extremely high density of bank-edge levees (>80%) add* 12

### Alteration of channel morphology and/or substrate

| A8 | Artificial changes of river course | | |
|---|---|---|---|
| A | Absence of artificial changes of river course in the past (meanders cut-off, channel diversions, etc.) | 0 | |
| B | Presence of changes of river course for ≤10% of the reach length | 2 | |
| C | Presence of changes of river course for >10% of the reach length | 3 | 41 |

| A9 | Other bed stabilization structures | | |
|---|---|---|---|
| A | Absence of structures (bed sills/ramps) and revetments absent or localised (≤5%) | 0 | |
| B | Sills or ramps (≤1 every *d*) and/or revetments ≤25% permeable and/or ≤15% impermeable | 3 | |
| C1 | Sills or ramps (>1 every *d*) and/or revetments ≤50% permeable and/or ≤33% impermeable | 6 | |
| C2 | Revetments >50% permeable and/or >33% impermeable | 8 | 44 |

*d=200 m in steep channels (S>1%); d= 1000 m in channels with S≤1%*

*In case of high density of bed revetment (impermeable >50% or permeable >80%) add* 6
*In case of extremely high density of bed revetment (impermeable >80%) add* 12

### Intervention of maintenance and removal

| A10 | Sediment removal | | | |
|---|---|---|---|---|
| A | Absence of recent (last 20 years) and past (last 100 years) significant sediment removal activities | 0 | | |
| B1 | Sediment removal activity in the past (last 100 years) but absent during last 20 years | 3 | | |
| B2 | Recent sediment removal activity (last 20 years) but absent in the past (last 100 years) | 4 | | |
| C | Sediment removal activity either in the past (last 100 years) and during last 20 years | 6 | 50 | M -2 |

*There is some uncertainty whether the activity in the past was significant.*

| A11 | Wood removal | | |
|---|---|---|---|
| A | Absence of removal of woody material at least during the last 20 years | 0 | |
| B | Partial removal of woody material during the last 20 years | 2 | |
| C | Total removal of woody material during the last 20 years | 5 | 52 |

*Not evaluated above the tree-line and in streams with natural absence of riparian vegetation (e.g. north-European tundra)*

## Morphological Quality Index (MQI)

| A12 | Vegetation management | | |
|---|---|---|---|
| A | No cutting interventions on riparian (last 20 years) and aquatic vegetation (last 5 years) | 0 | |
| B | Selective cuts and/or clear cuts of riparian vegetation ≤50% of the reach and partial or no cutting of aquatic vegetation, or no cutting of riparian but partial or total cutting of aquatic vegetation | 2 | |
| C | Clear cuts of riparian vegetation >50% of the reach, or selective cuts and/or clear cuts of riparian vegetation ≤50% of the reach but total cutting of aquatic vegetation | 5 | 52 |

*Riparian vegetation not evaluated above the tree-line and in streams with natural absence (e.g. north-European tundra)*
*Aquatic vegetation evaluated only in low-energy straight, sinuous, meandering or anabranching channels*

### CHANNEL ADJUSTMENTS

| CA1 | Adjustments in channel pattern | part. | prog. | conf. |
|---|---|---|---|---|
| A | Absence of changes of channel pattern from 1930s - 1960s | 0 | | |
| B | Change to a similar channel pattern from 1930s - 1960 | 3 | | |
| C | Change to a different channel pattern from 1930s - 1960s | 6 | 55 | |

*Not evaluated in the case of small streams where resolution of aerial photos is insufficient*

| CA2 | Adjustments in channel width | | |
|---|---|---|---|
| A | Absent or limited changes (≤15%) from 1930s - 1960s | 0 | |
| B | Moderate changes (15÷35%) from 1930s - 1960s | 3 | |
| C | Intense changes (>35%) from 1930s - 1960s | 6 | 61 |

*Not evaluated in the case of small streams where resolution of aerial photos is insufficient*

| CA3 | Bed-level adjustments | | |
|---|---|---|---|
| A | Negligible bed-level changes (≤0.5 m) | 0 | |
| B | Limited to moderate bed-level changes (0.5÷3 m) | 4 | |
| C1 | Intense bed-level changes (>3 m) | 8 | |
| C2 | Very intense bed-level changes (>6 m) | 12 | 65 |

*Not evaluated in the case of absolute lack of data, information and field evidence*

| | | | |
|---|---|---|---|
| **Total deviation:** | ***Stot =*** | 65 | 63÷67 |
| **Maximum deviation:** | ***Smax* = 142 - *Sna*=** | 139 | |
| *where Sna = sum of maximum scores for indicators that have not been applied* | | | |
| **Morphological Alteration Index:** | ***MAI = Stot / Smax =*** | 0.47 | 0.45÷0.48 |
| | *if Stot>Smax, MAI is assumed =1* | | |
| **Morphological Quality Index:** | ***MQI=1-MAI =*** | 0.53 | 0.52÷0.55 |
| **Quality class of the reach** | Moderate | | |

0≤*MQI*<0.3: Very Poor or Bad; 0.3≤*MQI*<0.5: Poor; 0.5≤*MQI*<0.7: Moderate;
0.7≤*MQI*<0.85: Good; 0.85≤*MQI*≤1.0: Very Good or High

5 of 5

# References

Berg, M.A., Allen, D.M., 2007. Low flow variability in groundwater-fed streams. Canadian Water Resources Journal, 32(3), 227-248.

Fontana, A., Mozzi, P., Marchetti, M., 2014. Alluvial fans and megafans along the southern side of the Alps. Sedimentary Geology, 301, 150-171.

Garófano-Gómez, V., Martínez-Capel, F., Bertoldi, W., Gurnell, A., Estornell, J., Segura-Beltrán, F., 2013. Six decades of changes in the riparian corridor of a Mediterranean river: a synthetic analysis based on historical data sources. Ecohydrology, 6(4), 536-553.

Gurnell, A.M., 2014. Plants as river system engineers. Earth Surface Processes and Landforms 39: 4-25.

Gurnell, A.M., van Oosterhout, M.P., de Vlieger, B., Goodson, J.M., 2006. Reach-scale interactions between aquatic plants and physical habitat: River Frome, Dorset. River Research and Applications, 22, 667-680.

Gurnell, A.M., O'Hare, J.M., O'Hare, M.T., Dunbar, M.J., Scarlett, P.M., 2010. An exploration of associations between assemblages of aquatic plant morphotypes and channel geomorphological properties within British rivers. Geomorphology, 116, 135-144.

Gurnell, A.M., O'Hare, M.T., O'Hare, J.M., Scarlett, P., Liffen, T.M.R., 2013. The geomorphological context and impact of the linear emergent macrophyte, Sparganium erectum L.: a statistical analysis of observations from British rivers. Earth Surface Processes and Landforms 38(15): 1869-1880.

Gurnell, A.M., O'Hare, M.T., Corenblit, D., García De Jalón, D., González Del Tánago, M., Grabowski, R., 2015. A conceptual model of vegetation-hydrogeomorphology interactions within river corridors'. River Research and Applications, in review.

Johnson, W.C., 1994. Woodland expansion in the Platte River, Nebraska, patterns and causes. Ecol. Monogr. 64: 45-84.

Jones, C.G., Lawton, J.H., Shachak, M., 1994. Organisms as ecosystem engineers. Oikos, 69, 373-386.

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

Liébault, F., Lallias-Tacon, S., Cassel, M., Talaska, N., 2012. Long profile responses of Alpine braided rivers in SE France. River Research and Applications, DOI: 10.1002/rra.2615.

Magdaleno, F., Fernandez-Yuste, J.A., 2013. Evolution of the riparian forest corridor in a large Mediterranean river system. Riparian Ecology and Conservation, 1, 36-45.

O'Hare, J.M., O'Hare, M.T., Gurnell, A.M., Dunbar, M.J., Scarlett, P.D., Laize, C., 2011. Physical constraints on the distribution of macrophytes linked with flow and sediment dynamics in British rivers. River Research and Applications, 27, 671-683.

Petts, G.E., Gurnell, A.M., 2013. Hydrogeomorphic effects of reservoirs, dams and diversions. In: Shroder, J. (Editor in chief), James, L.A., Harden, C.P., Clague, J.J. (Eds.), Treatise on Geomorphology. Academic Press, San Diego, CA, vol. 13, Geomorphology of Human Disturbances, Climate Change, and Natural Hazards, 96–114.

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

Rinaldi, M., Simon, A., 1998. Bed-level adjustments in the Arno River, central Italy. Geomorphology 22, 57-71.

Sennatt, K.M., Salant, N.L., Renshaw, C.E., Magilligan F.J., 2008. Assessment of methods for measuring embeddedness: application to sedimentation in flow regulated streams. Journal of American Water Resources Association 42(6), 1671-1682.

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

Surian, N., Rinaldi, M., Pellegrini, L., Audisio, C., Maraga, F., Teruggi, L., Turitto, O., Ziliani, L., 2009. Channel adjustments in northern and central Italy over the last 200 years. In: James L.A., Rathburn S.L., Whittecar G.R. (eds.), Management and Restoration of Fluvial Systems with Broad Historical Changes and Human Impacts, Geological Society of America Special Paper 451, pp. 83-95.

Wyżga, B., 2008. A review on channel incision in the Polish Carpathian rivers during the 20th century. In: Habersack, H., Piégay, H., Rinaldi, M. (Eds), Gravel-Bed Rivers VI – From process understanding to river restoration, Developments in Earth Surface Processes, 11, Elsevier, pp. 525-555.

# Appendix 4: Illustrated Guide to the Compilation of the Evaluation Forms

## *Generality and delineation of spatial units*

### 1. Physiographic setting

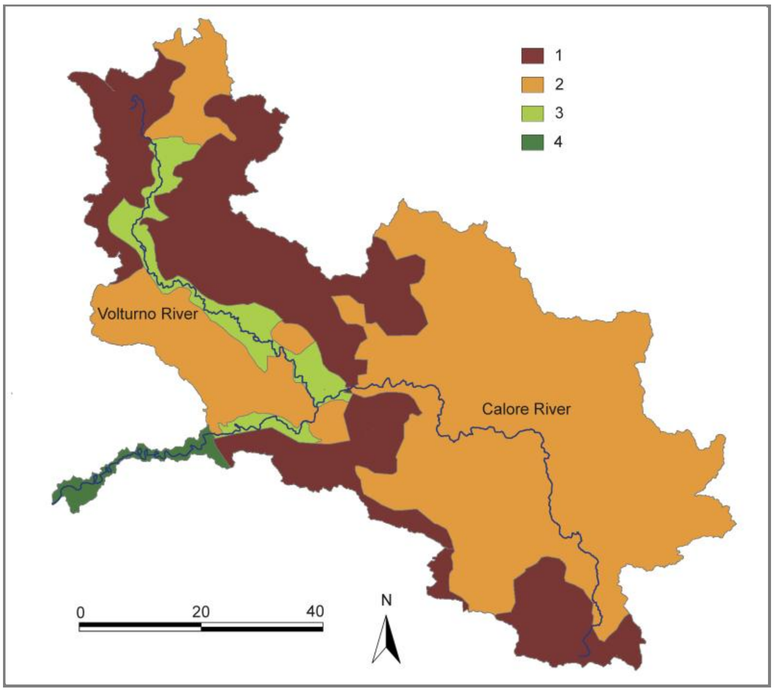



**Figure 1 Delineation of the catchment of the Volturno River (Italy) into landscape units. (1) Mountainous unit; (2) Hilly unit; (3) Intermontane plain unit; (4) Low plain unit.**

1 2

3 4

**Figure 2 Panoramic views of the landscape units in the Volturno River catchment. (1) Mountainous unit; (2) Hilly unit; (3) Intermontane unit; (4) Low plain unit.**

## 2. Confinement

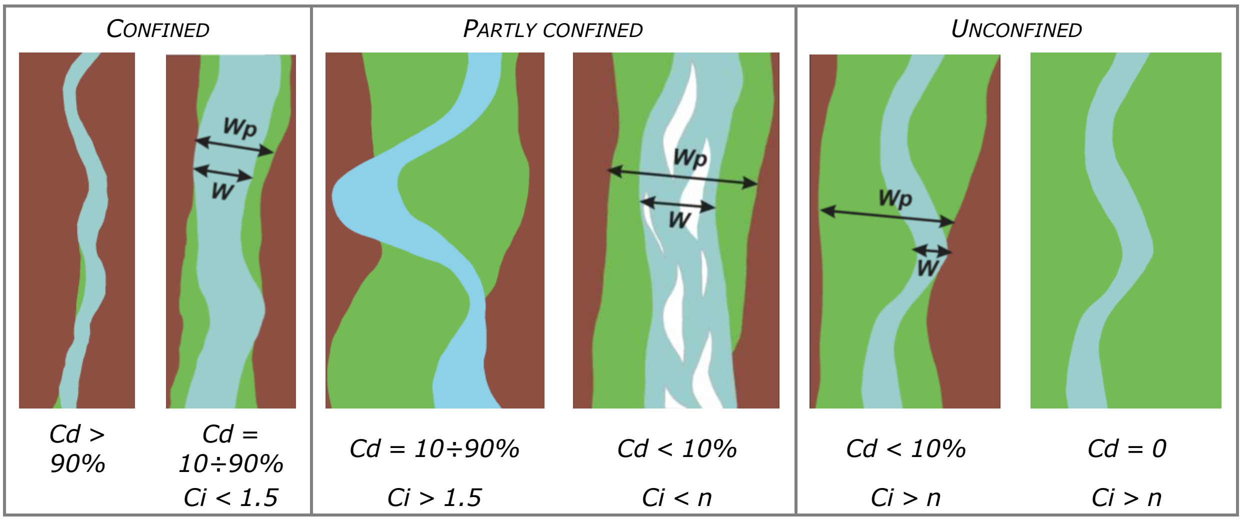



**Figure 3 Confinement classes. In green: floodplain; in brown: hillslopes (or ancient terraces). *Cd*: confinement degree; *Ci*: confinement index = *Wp/W*, where *Wp*: floodplain width (including the channel) and *W*: channel width.**


**Figure 4 Examples of different confinement classes. (1), (2) Confined channels; (3), (4) partly confined channel.**


**Figure 4** *(continued)* **Examples of different confinement classes. (5), (6) unconfined channels.**

## 3. Channel morphology

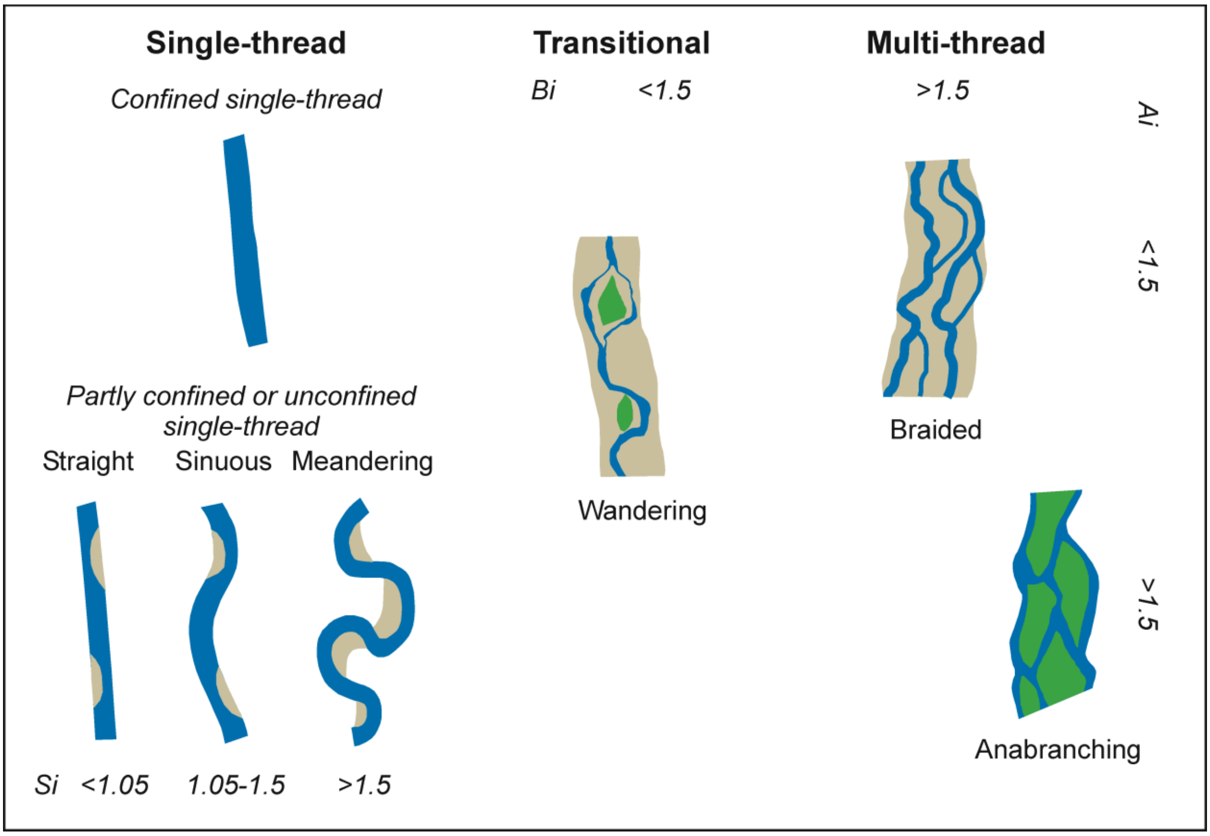



**Figure 5 Channel morphologies. *Si*: sinuosity index; *Bi*: braiding index; *Ai*: anabranching index.**

Partly confined and unconfined channels

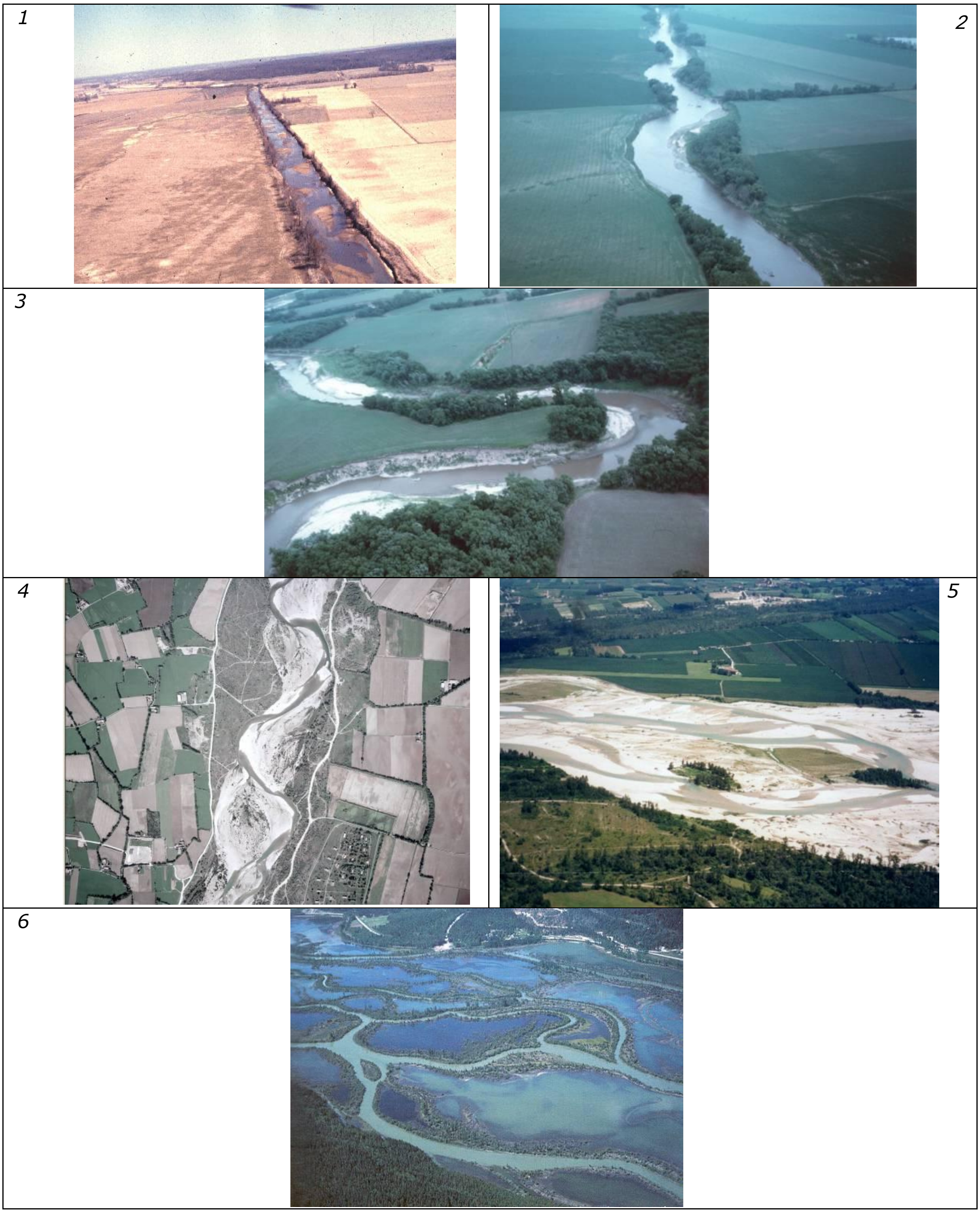



**Figure 6 Examples of morphologies of partly confined and unconfined channels. (1) Straight; (2) sinuous; (3) meandering; (4) wandering; (5) braided; (6) anabranching (the islands and floodplain are inundated).**

*Confined channels*


**Figure 7  Morphologies of confined channels. (1) Confined single-thread; (2) confined wandering; (3) confined braided; (4) confined anabranching.**

*Bed configuration*

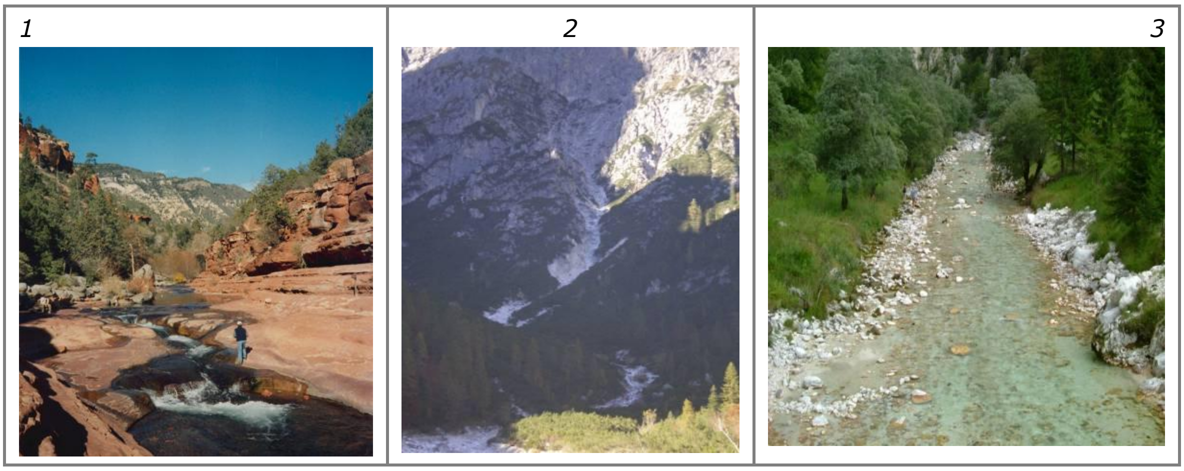



**Figure 8  Initial distinction of bed configuration at reach scale. (1) Bedrock channel; (2) colluvial channel; (3) alluvial channel.**

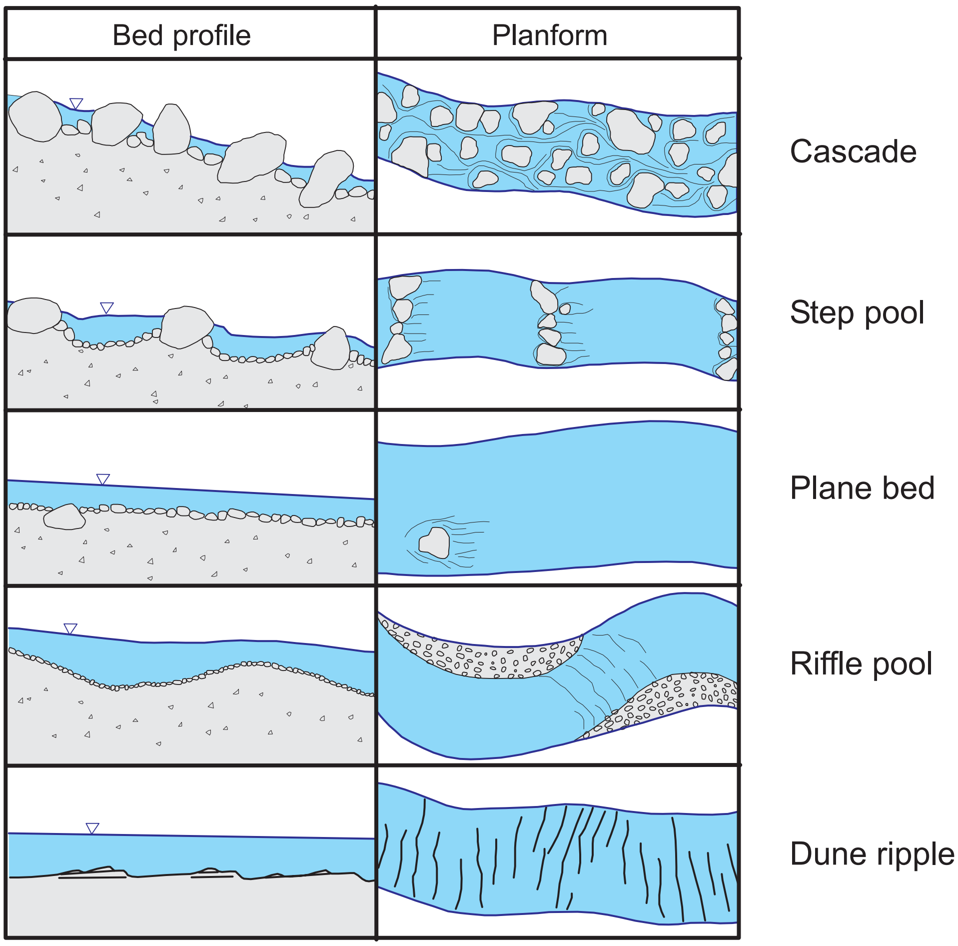



**Figure 9 Classification of bed configuration at reach-scale in single-thread, alluvial channels (modified from Montgomery & Buffington, 1997).**

**Table 1 Characteristic geomorphic units defining the bed configuration of alluvial channels at reach scale.**

| Reach scale | Geomorphic Units |
|---|---|
| **CASCADE** | **CASCADES** |
| **STEP POOL** | **STEPS, POOLS** |
| **PLANE BED** | **RAPIDS, GLIDES** |
| **RIFFLE POOL** | **RIFFLES, POOLS, GLIDES** |
| **DUNE RIPPLES** | **DUNE, RIPPLES** |


**Figure 10 Reach-scale morphologies in single-thread, alluvial channels. (1) Cascade; (2) step pool; (3) plane bed; (4) riffle pool; (5) dune ripple.**

## 4. Other elements for reach delineation

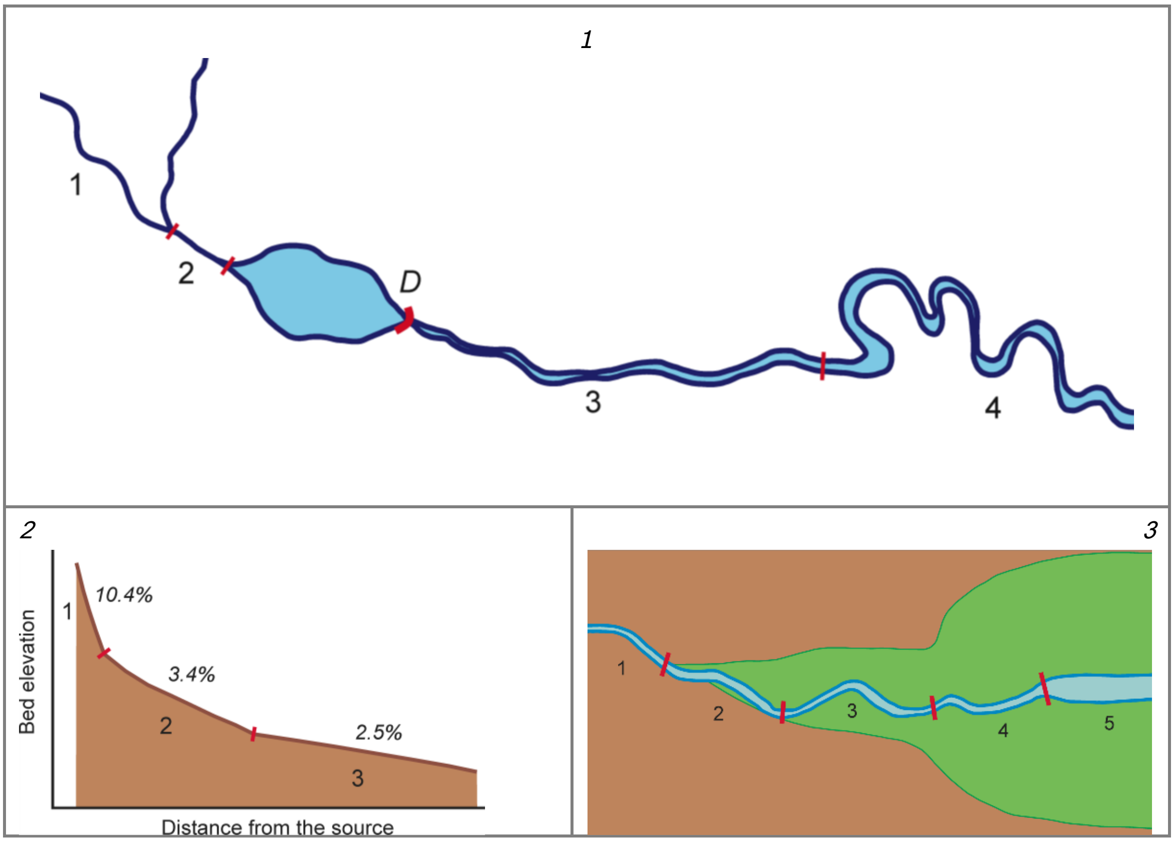



**Figure 11 Examples of discontinuities considered during the final step of segmentation. (1) Hydrological discontinuity due to a major tributary (reaches 1 and 2); dam (D) (reaches 2 and 3: note that the reservoir is not considered as a river reach). (2) Discontinuity in bed slope (confined reaches). (3) Other discontinuities that can be used for river segmentation: change in size of the floodplain (from 3 to 4); change in channel width (from 4 to 5).**

## *Geomorphological Functionality*

### <u>Continuity</u>

### F1: Longitudinal continuity in sediment and wood flux

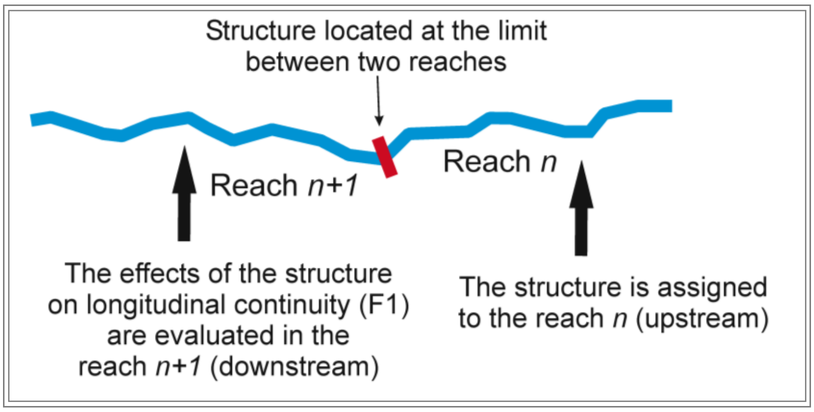



**Figure 12 Longitudinal continuity in sediment and wood flux. Rule of assignation of a transversal structure located at the limit between two reaches, and its effects on longitudinal continuity.**

<u>*Confined channels*</u>

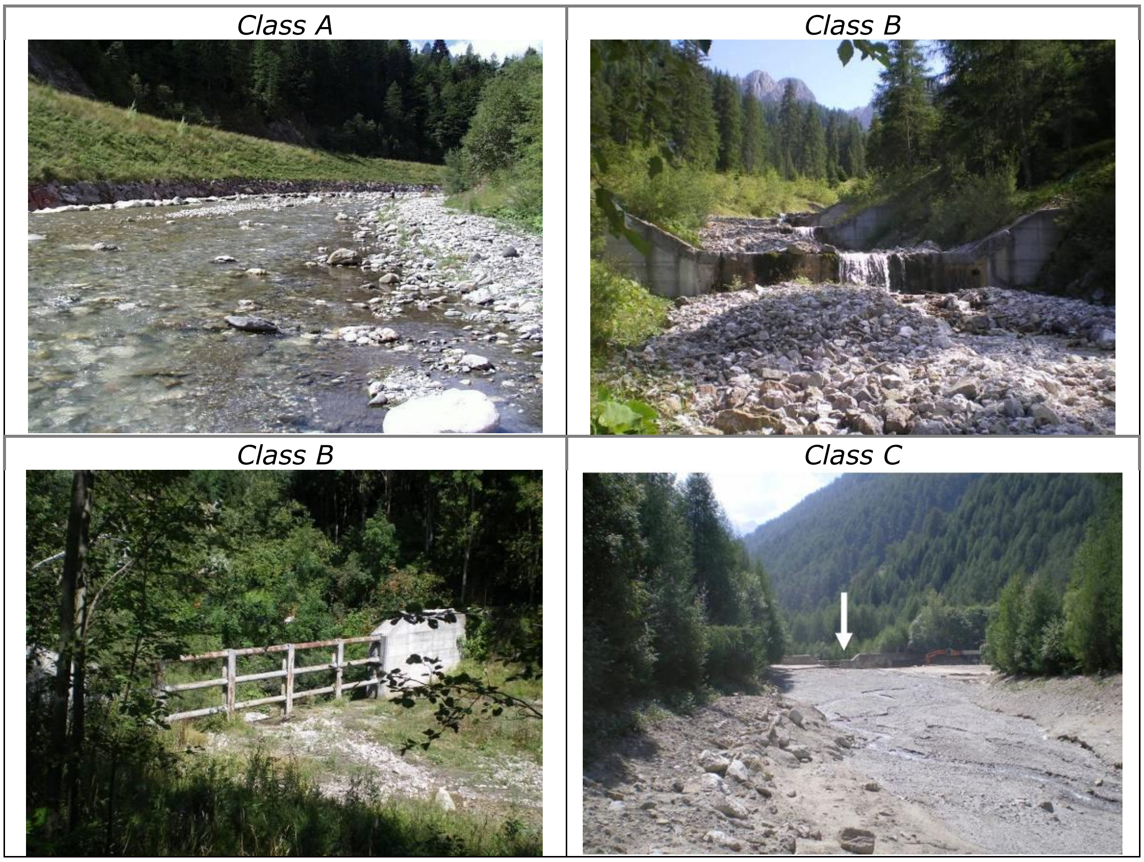



**Figure 13 Longitudinal continuity in sediment and wood flux. *Class A*: absence of discontinuities. *Class B*: up on the right, filled consolidation check dams; low on the left, open check dam. *Class C*: a check dam (arrow) with total interception represents a complete alteration of longitudinal continuity in the reach downstream from the check dam.**

*Partly confined and unconfined channels*

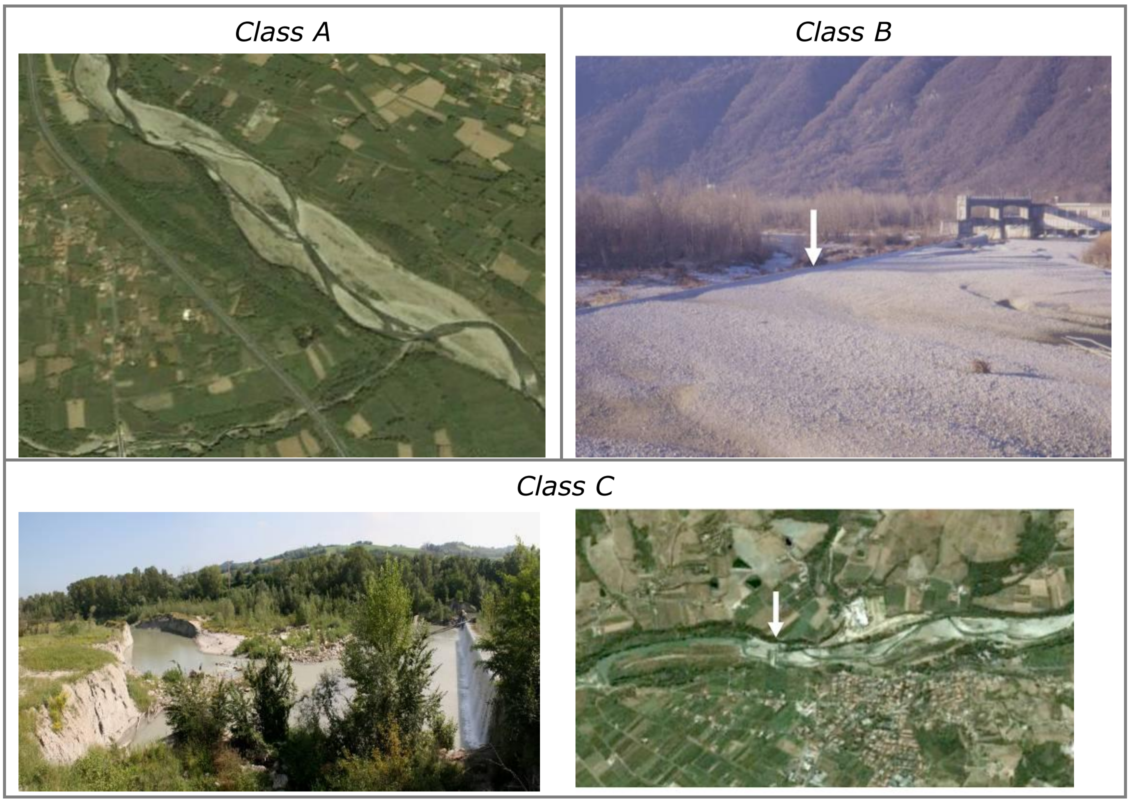



**Figure 14 Longitudinal continuity in sediment and wood flux. *Class A*: absence of discontinuities. *Class B*: filled check dam (arrow) altering the normal flux of sediment but without causing total interception and a discontinuity of forms (bars are observed either upstream and downstream). *Class C*: presence of a weir or check dam with total sediment interception resulting in a significant alteration of the reach immediately downstream (the river flows from right to left).**

## F2: Presence of a modern floodplain

*Terminology*


**Figure 15 Differences between a modern floodplain and a recent terrace. (1) and (2) Examples of modern floodplain (note the very limited differences in elevation with channel bars); 3: recent terrace generated by a bed incision of about 2÷3 m; 4: recent terrace generated by an intense incision (> 3 m).**

*Interactions with other indicators*

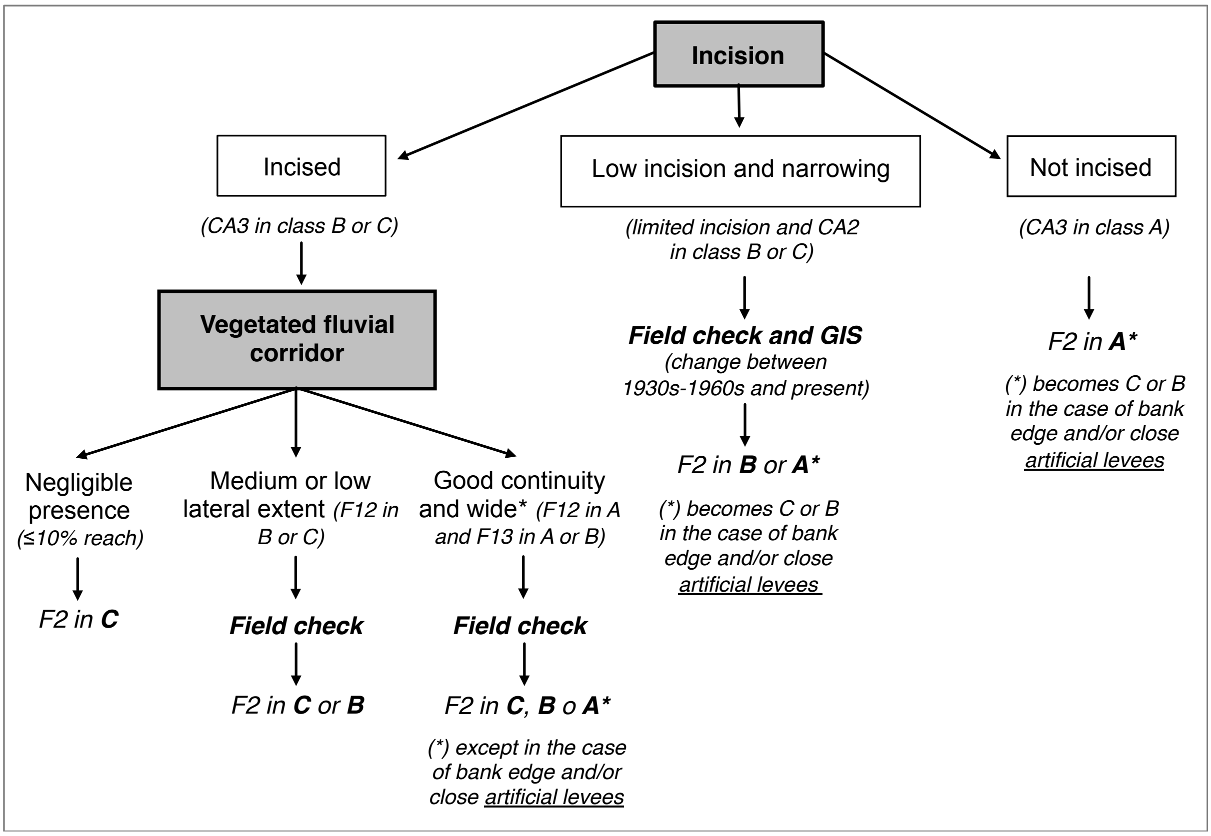



**Figure 16 Sketch of interactions among different indicators to support the classification of *F2*. *Class B* may correspond to *B1* or *B2*, depending on the width of the floodplain (see Figure 1 of the Guide to the Compilation of the Evaluation Forms).**

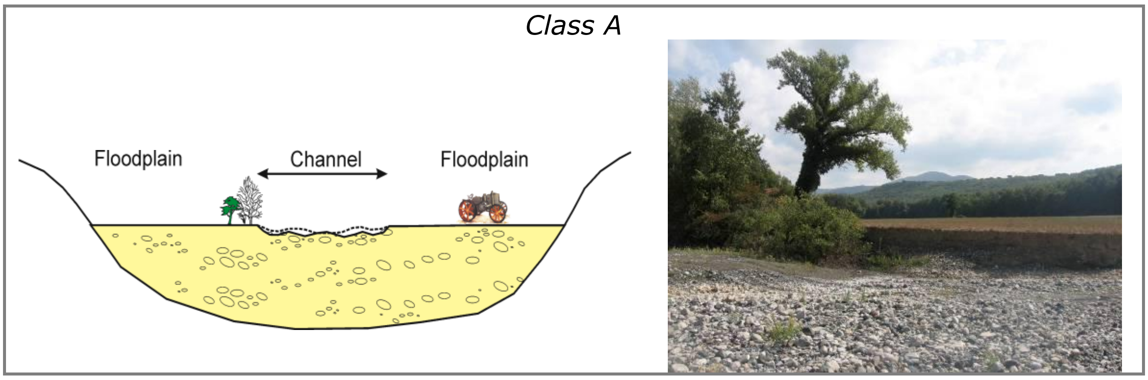



**Figure 17 Case 1: the channel is not incised (*V3* in *Class A*), therefore the adjacent alluvial surface corresponds to a modern floodplain (*Class A*).**

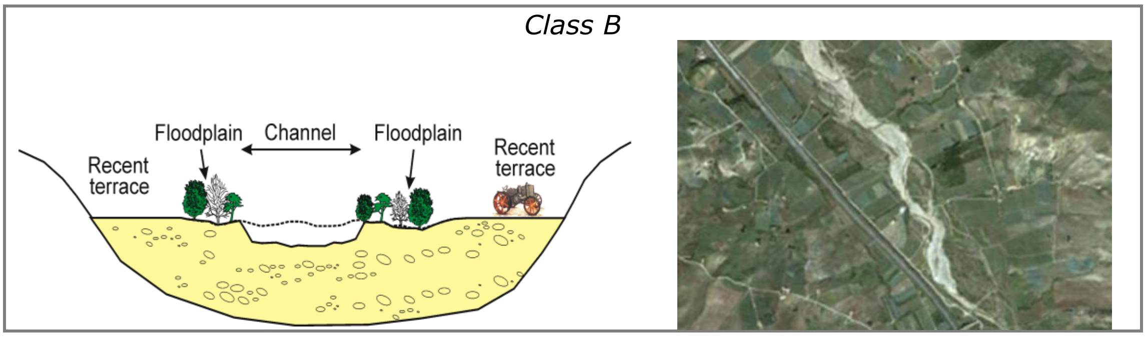



**Figure 18 Case 2: the channel is slightly incised and narrowed compared to 1930s-60s. Vegetation in the fluvial corridor is quite wide (*F12* in *Class B*) and mostly coincides with the channel of 1930s-60s. The field assessment enables verification that the vegetation corridor coincides with the modern floodplain, resulting therefore in *Class B* (*B1* or *B2*, depending on the floodplain width).**

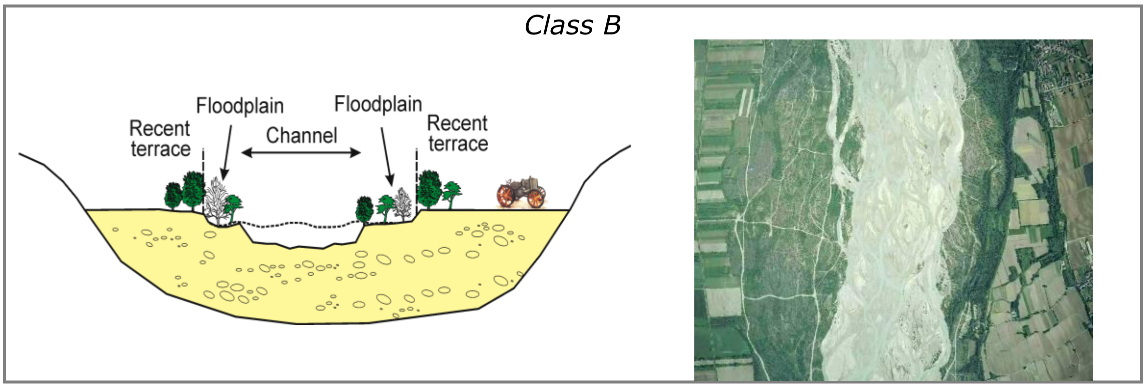



**Figure 19 Case 3: the channel is moderately incised and slightly narrowed compared to 1930s-60s. Vegetation corridor is continuous and wide (*F12* and *F13* in *Class A*). Field assessment enables verification that the vegetation corridor also includes portions of recent terraces, therefore the floodplain is not sufficiently wide (*Class B1* or *B2*).**

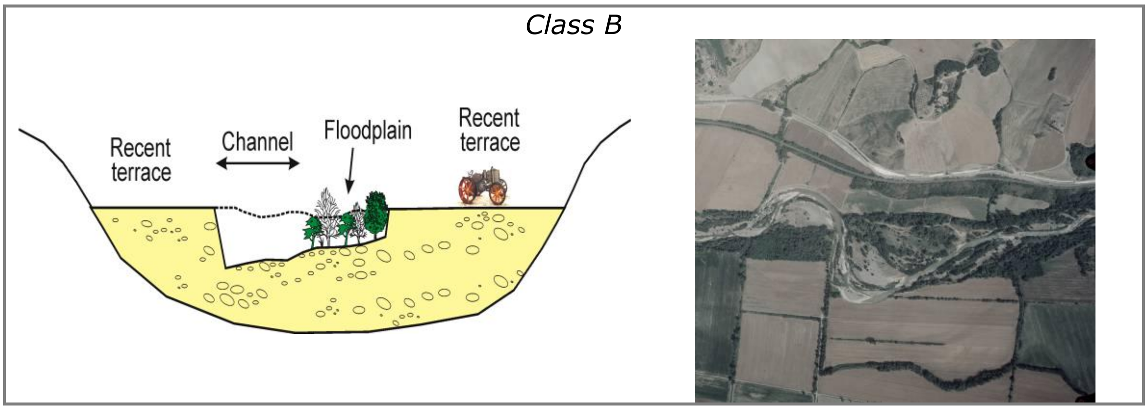



**Figure 20 Case 4: the channel is incised and the vegetation corridor has a medium width (*F12* in *Class B*). Field assessment enables verification that most of the vegetations corridor corresponds to a modern floodplain formed after incision as consequence of lateral mobility (*Class B1* or *B2*).**

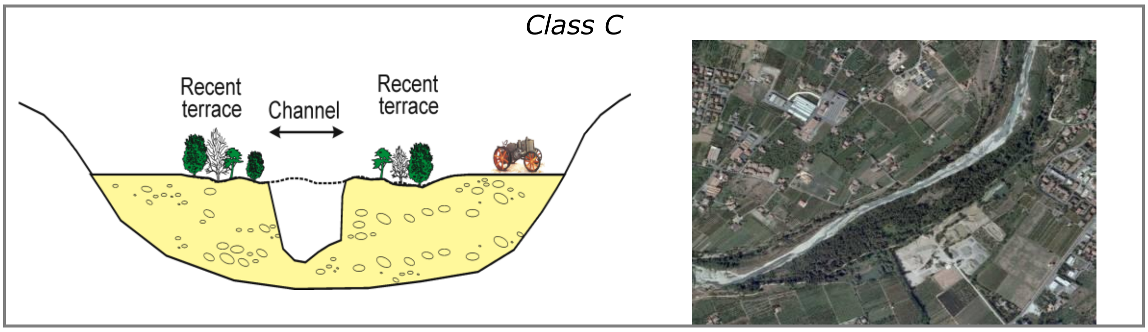



**Figure 21 Case 5: the channel is heavily incised (> 6 m) and narrowed, and the vegetation corridor has a medium width (*F12* in *Class B*). Field assessment enables verification that the vegetation in this case occupies portions of the 1930s-60s channel disconnected by the present channel (recent terraces) (*Class C*).**

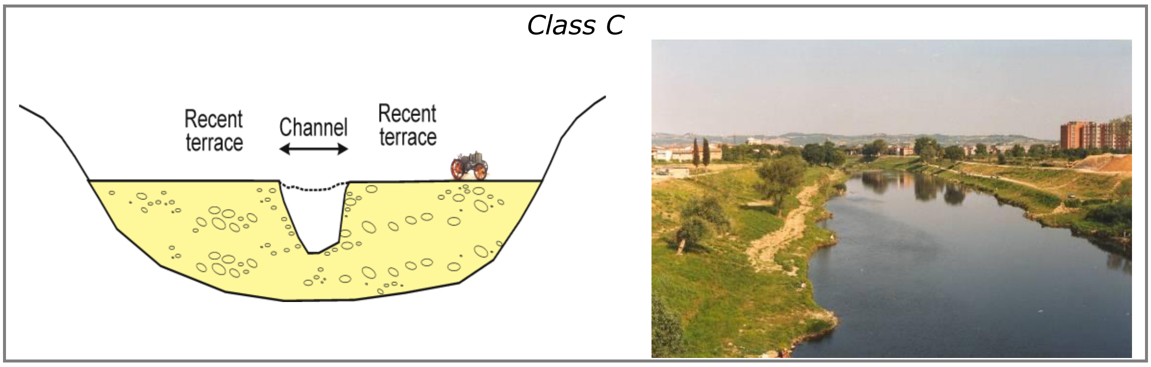



**Figure 22 Case 6: the channel is heavily incised (> 6 m) and vegetation corridor that could be a post-incision floodplain is absent (*F12* in *Class C*), therefore the reach is necessarily in *Class C*.**

## F3: Hillslope – river corridor connectivity

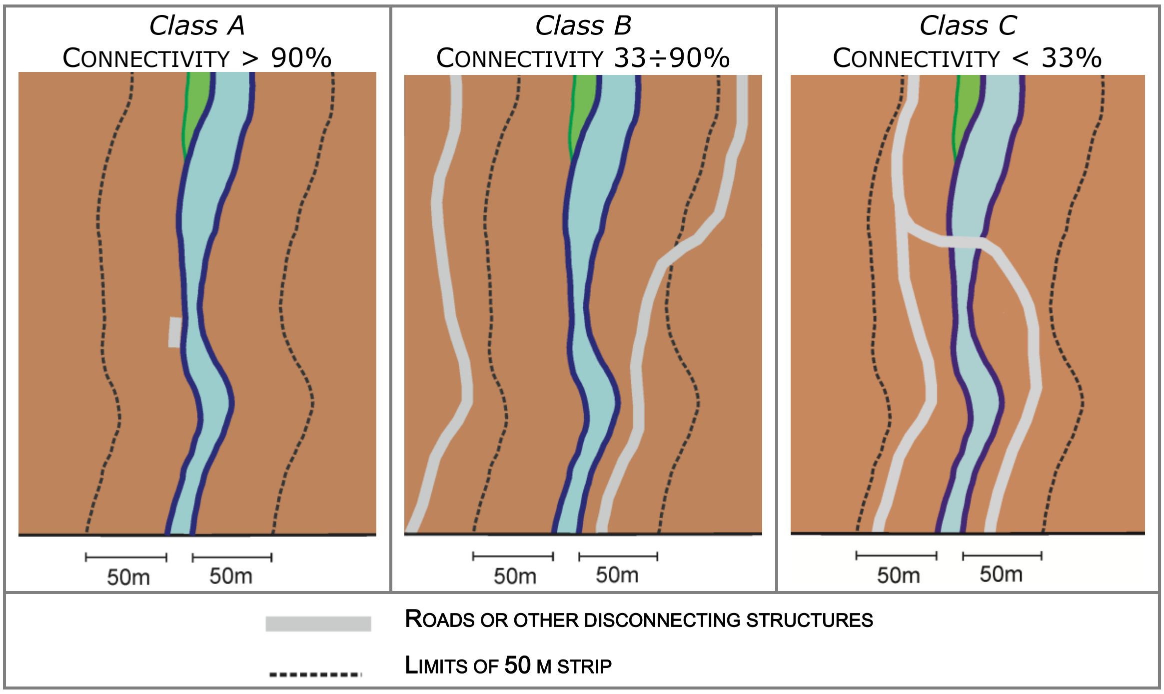



**Figure 23 Connectivity between hillslopes and fluvial corridor. *Classes* as a function of the link between stream and adjacent hillslopes for a strip 50 m wide on both sides.**

## F4: Processes of bank retreat

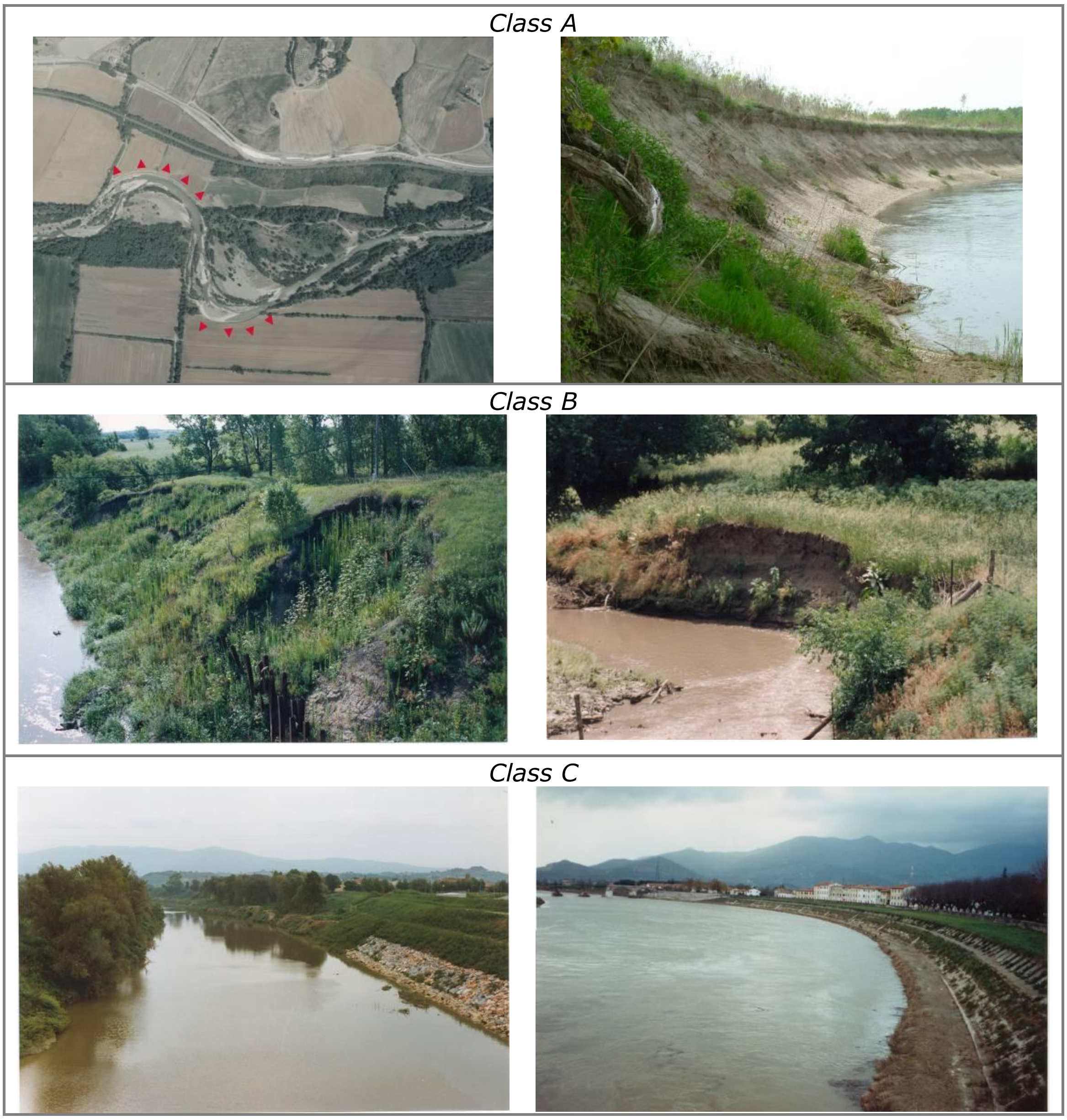



**Figure 24 Processes of bank retreat. *Class A*: frequent retreating banks (red arrows, photo on the left), as expected for the river typology. *Class B*: bank erosion occurs less frequently than expected for the river typology. *Class C*: complete absence or very localized presence of eroding banks due to excessive human control.**

*Class C*

**Figure 24** ***(continued) Class C*****: significant presence of unstable, eroding banks by mass failure related to an excessive bank height because of bed incision.**

## F5: Presence of a potentially erodible corridor

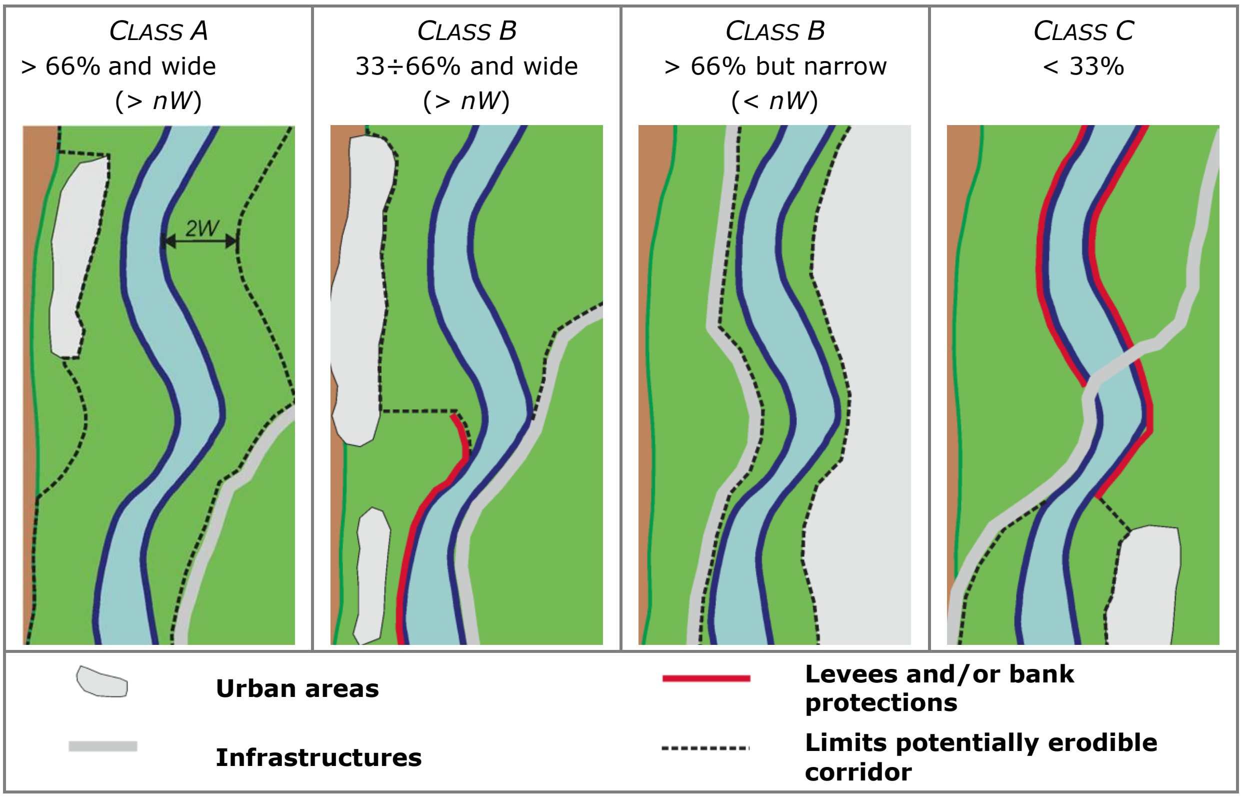



**Figure 25 Potentially erodible corridor. *Class A*: notwithstanding the constructed area and the road, a continuous and sufficiently wide erodible corridor exists. *Class B*: the erodible corridor is wide (mean width in the reach > *nW*) but with medium longitudinal continuity (33÷66%) (second figure from left), or it is continuous (> 66%) but not sufficiently wide (mean width < *nW*) (third figure from left). *Class C*: a potentially erodible corridor (of any width) exists only for < 33% of the reach.**

## Morphology

### F6: Bed configuration – valley slope

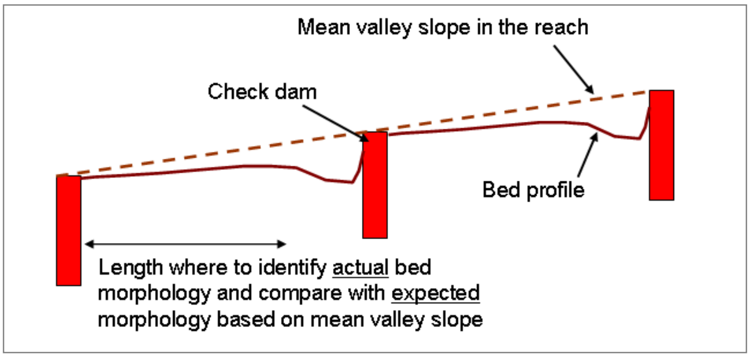



**Figure 26 Bed configuration and valley slope. Rule for the measurement of the mean valley slope of the reach in the presence of structures (check dams) and to identify the length of analysis of bed morphology.**

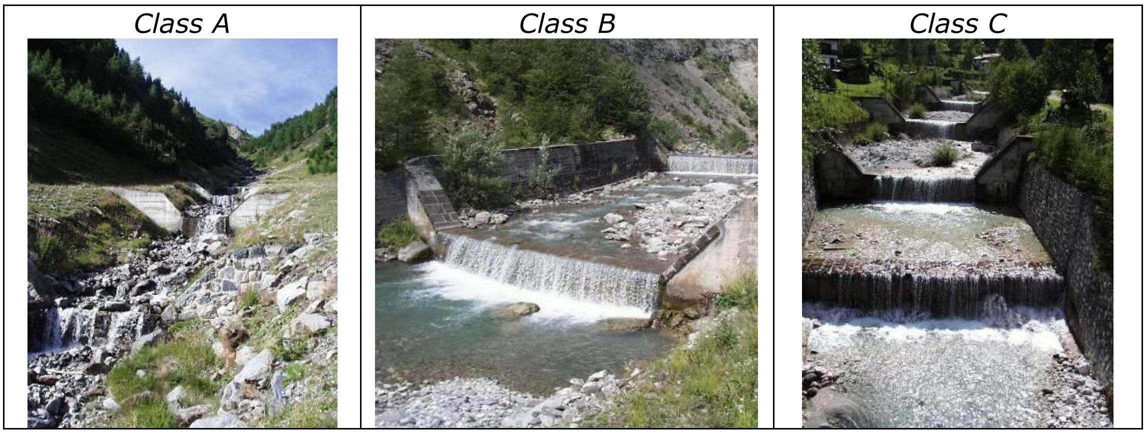



**Figure 27 Bed configuration and valley slope. *Class A*: consolidation check dams that do not alter the expected bed configuration based on valley slope (step pool in both cases). *Class B*: the consolidation check dams determine a bed configuration (plane bed) different from the expected one (cascade / step pool). *Class C*: complete alteration of bed configuration, due to distance between transversal structures being too close, not allowing the creation of natural bed forms (except the scour pool downstream from the structures).**

## F7: Planform pattern

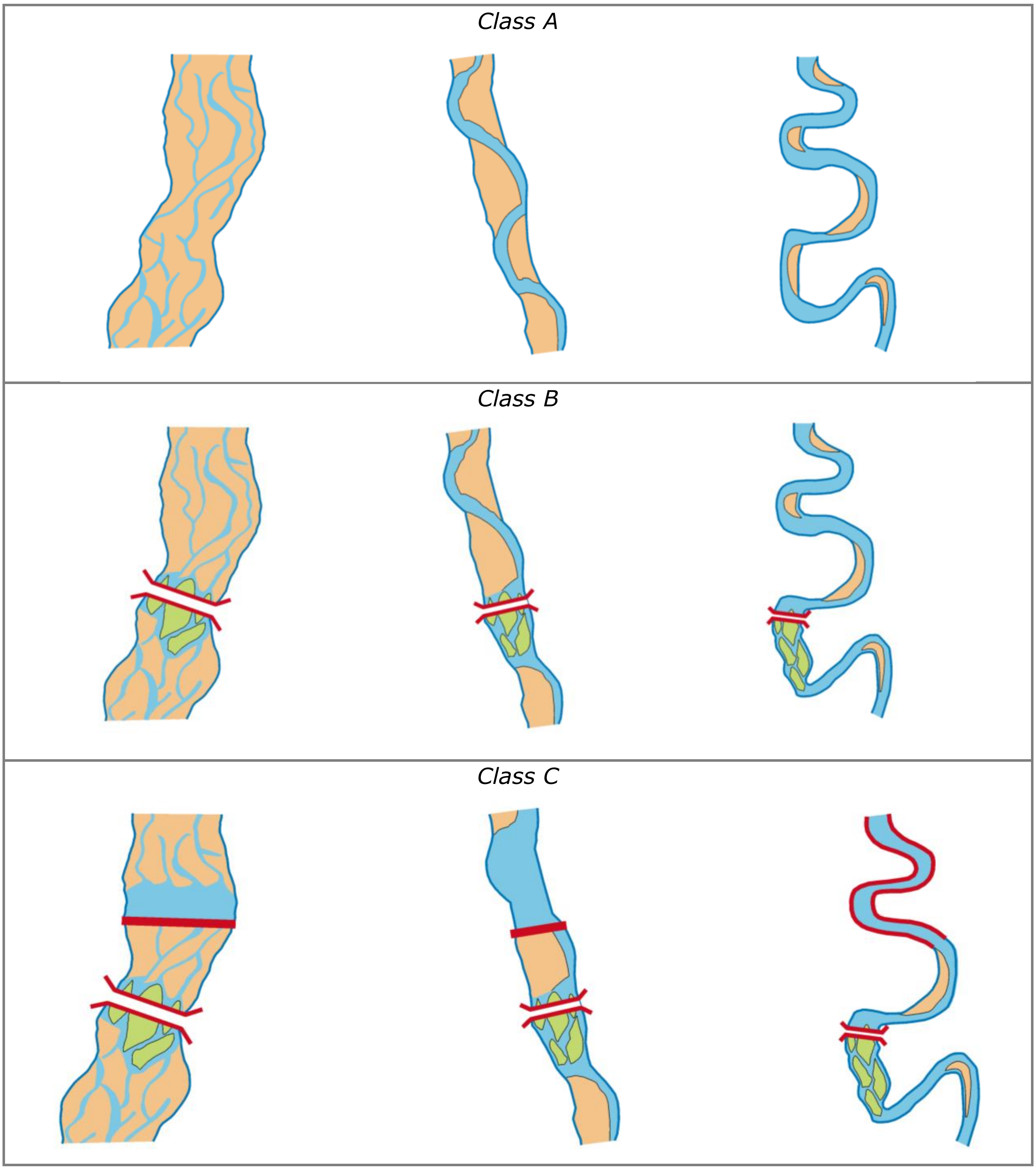



**Figure 28 Planform pattern: examples for multi-thread, transitional, and single-thread channels. *Class A*: absence of alterations. *Class B*: a bridge can alter the morphological pattern (< 33% of the reach) by the formation of islands. *Class C*: in case of a braided or transitional channel, a bridge and a check dam can produce significant alterations in the reach (> 33%). In the case of a single-thread channel, bank protections cause a loss of the geomorphic units and of the longitudinal variability in channel width, although the conservation of a meandering planimetric pattern.**

## F8: Presence of typical fluvial landforms in the floodplain

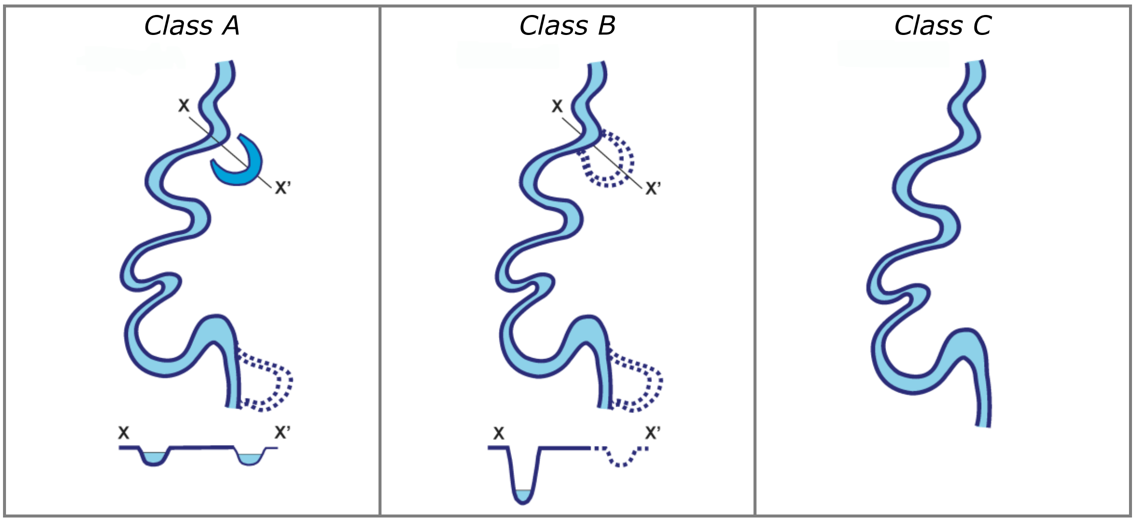



**Figure 29 Presence of typical fluvial forms in the alluvial plain. *Class A*: presence of natural fluvial forms (e.g. abandoned meander, oxbow lake). *Class B*: traces of fluvial forms, now disconnected by the channel due to incision, but with possible reactivation. *Class C*: complete absence of fluvial forms in the alluvial plain.**

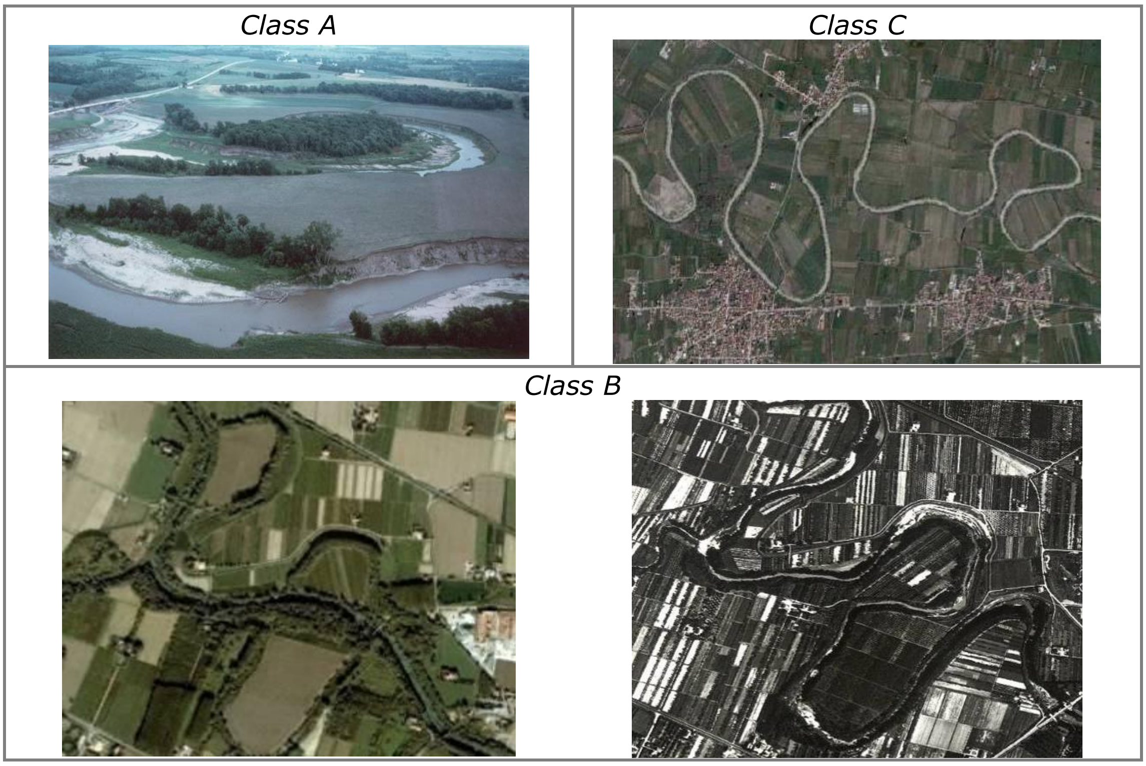



**Figure 30 Presence of typical fluvial forms in the floodplain. *Class A*: meandering river with a recent cut-off. *Class C*: meandering river with complete absence of landforms in the plain. *Class B*: traces of abandoned meanders exits (photo on the left), disconnected from the channel because of bed incision. The observation of the aerial photos of the 1950's (photo on right) enables verification that these forms have been abandoned during the last decades.**

## F9: Variability of the cross-section

*Confined channels*

| *Class A* | *Class B* |
|---|---|
|  |  |
| *Class B* | *Class C* |
|  |  |

**Figure 31 Variability of the cross-section in confined channels. *Class A*: absence of alterations of the natural heterogeneity in the cross-section. *Class B* (photo top right): alterations for a limited portion of the reach. *Class B* (photo bottom left): alterations on a substantial portion of the reach but only on one side (bank wall). *Class C*: complete alteration of the natural heterogeneity in the cross-section due to bank walls on both sides.**

*Partly confined and unconfined channels*

1

2

**Figure 32 Alteration of cross-section variability in partly- and unconfined channels. (1) Cases of partial homogenization of the cross-section due to interventions. (2) Cross-section homogeneity extended for long reaches due to excessive artificiality.**

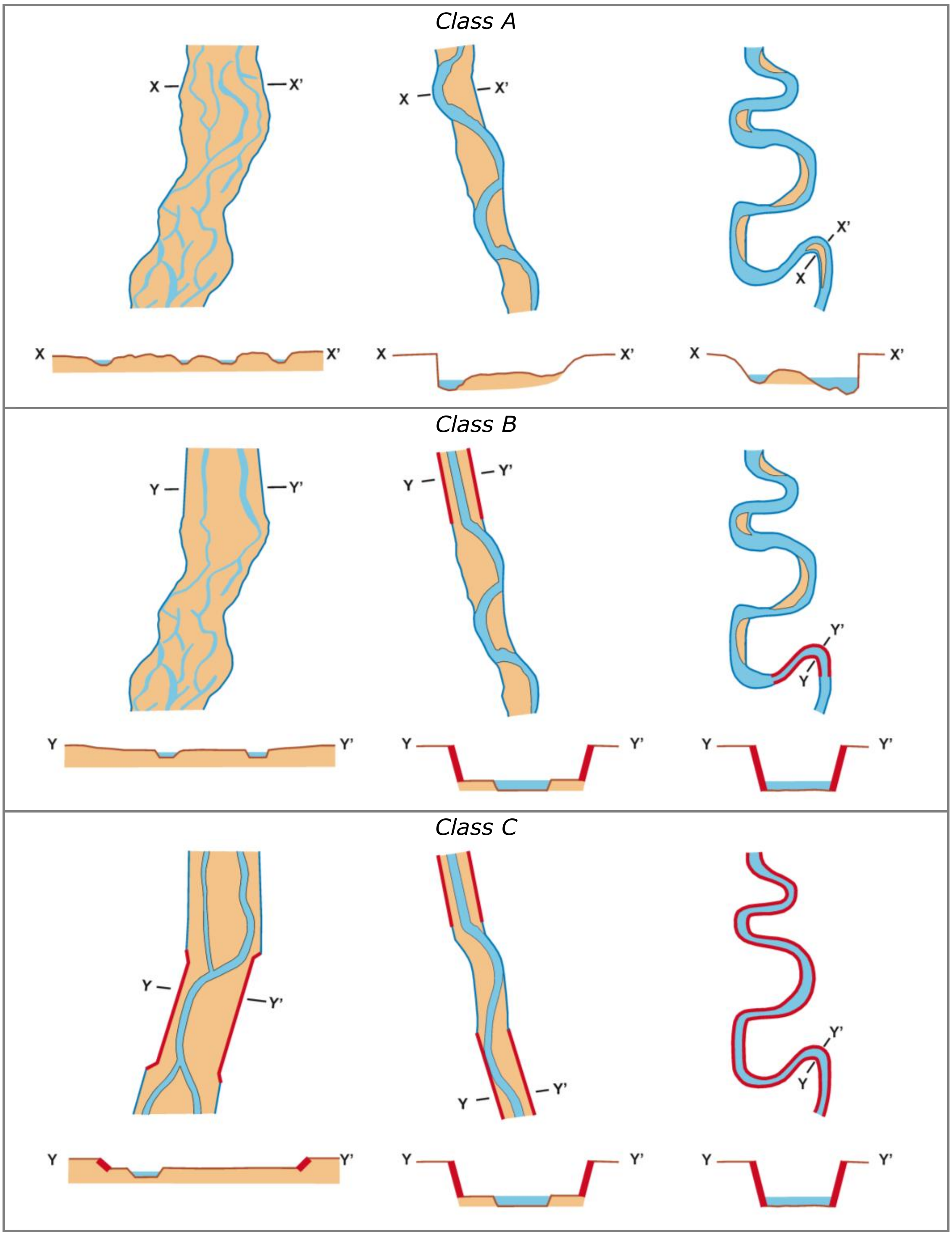



**Figure 33 Variability of the cross-section in partly- and unconfined channels: examples for multi-thread, transitional, and single-thread channels. *Class A*: absence of alterations. *Class B*: alterations for a portion < 33% of the reach length. *Class C*: alterations for a portion > 33% of the reach length.**

## F10: Structure of the channel bed

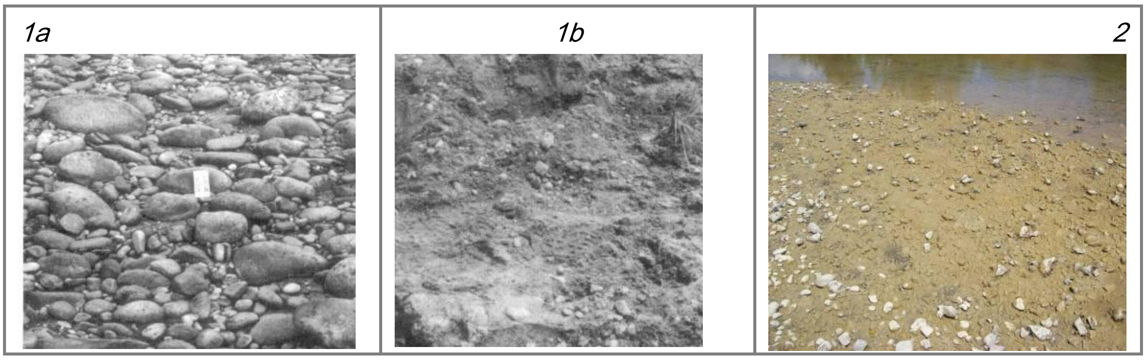



**Figure 34 Alterations of the substrate. (1) Armouring (*a*: superficial layer; *b*: sub-layer). (2) Clogging.**

*Confined channels*

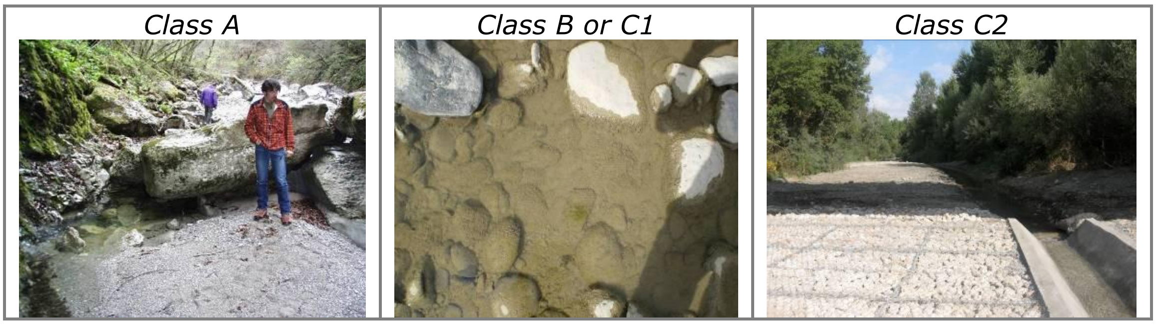



**Figure 35 Alteration of substrate in confined channels. *Class A*: natural heterogeneity of substrate in a confined channel. *Class B* or *C1*: presence of clogging (the assignation to *Class B* or *C1* will depend on its extension in the reach). *Class C2*: complete alteration of substrate because of widespread bed revetments.**

*Partly confined and unconfined channels*


**Figure 36 Alterations of substrate in partly- and unconfined channels. *Class A*: natural sediment heterogeneity in an unconfined channel. *Class B* or *C1*: presence of armouring (photo on left) or clogging (photo on right) (assignation to *Class B* or *C1* will depend on the extension of armouring and/or clogging along the reach). *Class C2*: bedrock outcroppings due to bed incision (photo on left) or completely altered substrate because of bed revetment (photo on right).**

## F11: Presence of in-channel large wood


**Figure 37 Presence of large wood. *Class A*: natural presence of large wood in a steep confined channel with limited width and (cascade, first row on left), and in a wider and less steep confined channel with (plane bed morphology, center); natural absence of riparian vegetation and large wood because the reach is above the tree-line (right); natural presence of large wood in unconfined channels (photos in central row). *Class B or C*: examples of channels with absence of large wood because of recent interventions of removal (photos in the lower row) (assignation to *Class B* or *C* will depend on the extension of the alteration along the reach).**

Vegetation in the fluvial corridor


**Figure 38 Vegetation in the fluvial corridor. (1) Presence of vegetation connected with the channel in a partly confined reach; (2) absence of vegetation (right) or vegetation disconnected by the stream channel because of the presence of walls.**

### F12: Width of functional vegetation

*Confined channels*

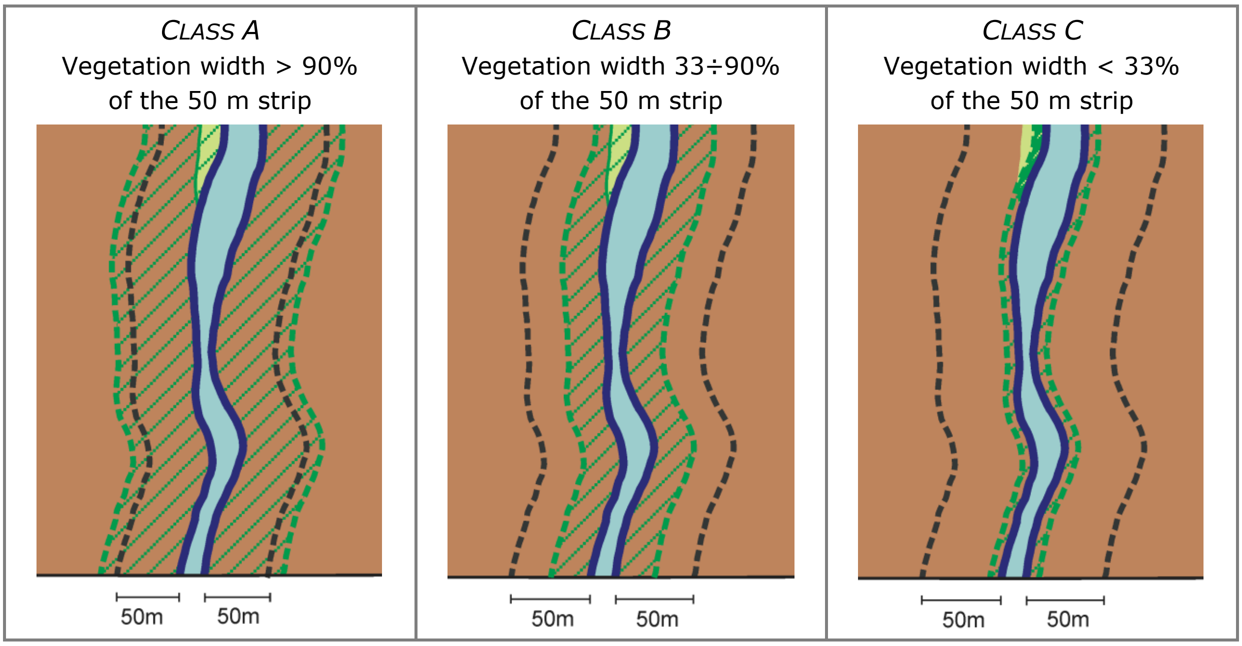



**Figure 39 Width of functional vegetation in confined channels. *Class A*: the vegetation corridor occupies > 90% of the plain and adjacent hillslopes (for a strip of 50 m for each side, represented by the dotted black line). *Class B*: the vegetation corridor is between 33 and 90%. *Class C*: the vegetation corridor is extremely limited (< 33%).**

*Partly confined and unconfined channels*

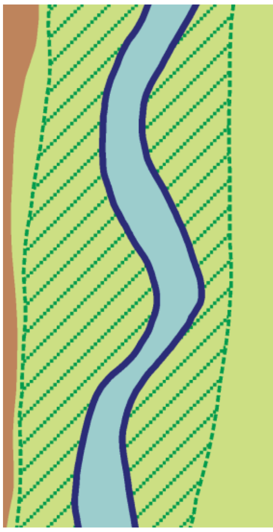
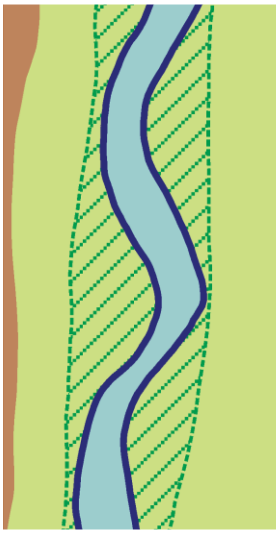
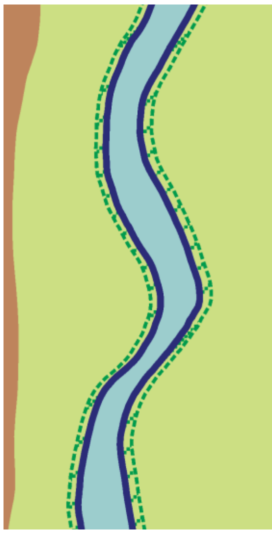
| *CLASS A* Vegetation width > *nW* | *CLASS B* Vegetation width 0.5*W*÷ *nW* | *CLASS C* Vegetation width < 0.5*W* |
|---|---|---|
|  |  |  |

**Figure 40 Width of fluvial corridor in partly- and unconfined channels. *Class A*: the vegetation corridor is sufficiently wide, having a width > *nW* (*W*: mean channel width); *Class B*: the vegetation corridor has a medium width, being included between 0.5*W* and *nW*; *Class C*: the vegetation corridor is extremely narrow, having a width < *0.5W*.**

| *Class A* | *Class B* | *Class C* |
|---|---|---|
|  |  |  |

**Figure 41 Width of functional vegetation in partly confined and unconfined channels. *Class A*: the vegetation corridor is very wide compared to the channel width. *Class B*: the vegetation corridor has a medium width. *Class C*: the vegetation corridor is almost absent.**

## F13: Linear extension of functional vegetation and presence of emergent aquatic macrophytes

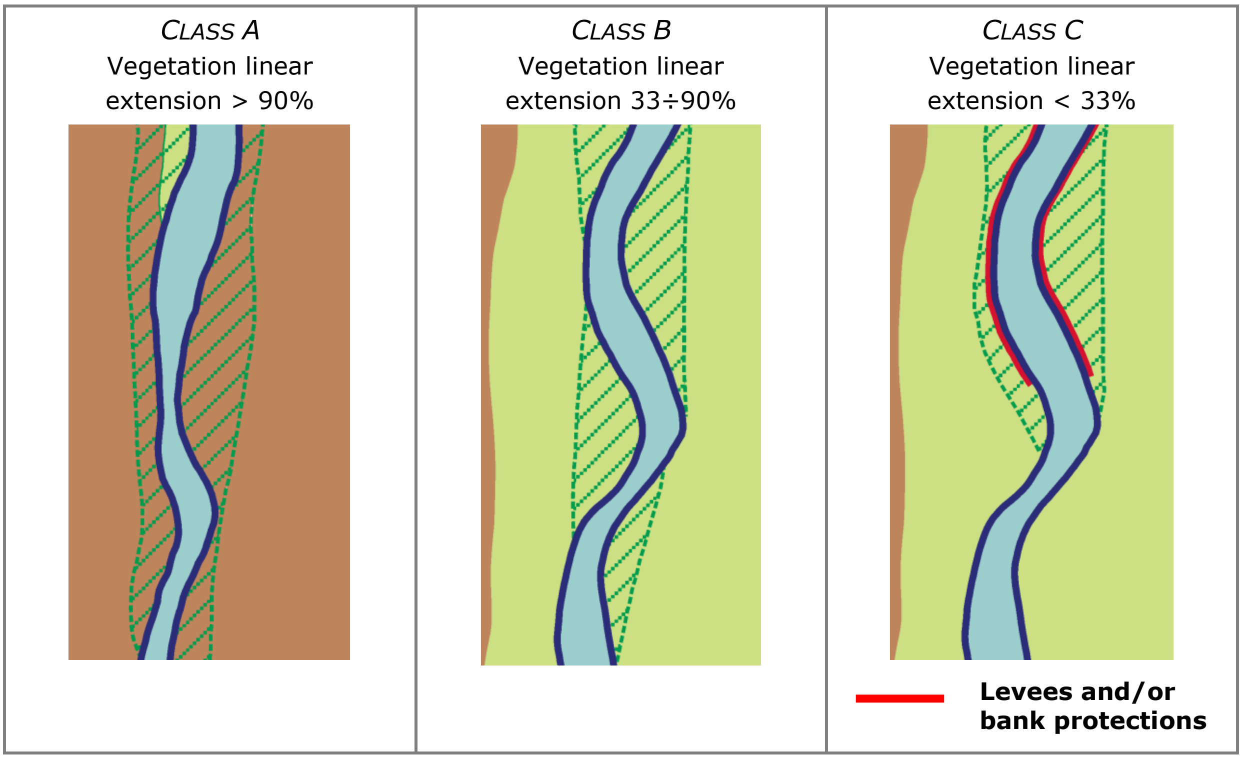



**Figure 42 Linear extension of the functional vegetation along the banks. *Class A*: the linear extension is very high (> 90% of the total length of both banks). *Class B*: the linear extension is lower than 90% but higher than 33%. *Class C*: although a vegetation corridor exists for about half of the reach, most of it is disconnected because of the existence of artificial levees and/or bank protections.**

**Figure 43 Presence of emergent aquatic macrophytes is evaluated in the indicator *F13* only in the case of low-energy sinuous, meandering or anabranching channels (see *Guide for Compilation of the Evaluation Forms* for details).**

## *Artificiality*

<u>Upstream alteration of longitudinal continuity</u>

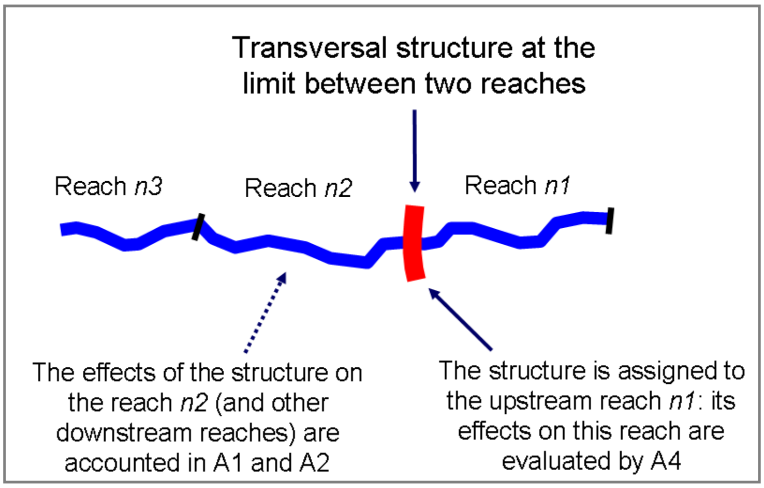



**Figure 44 Rule of assignation of a transversal structure coinciding with the limit between two reaches and its effects on the alteration of sediment and water discharges.**

### A1: Upstream alteration of flows


**Figure 45 Alteration of flows. Typical alteration structures. (1) Dam; (2) spillway.**

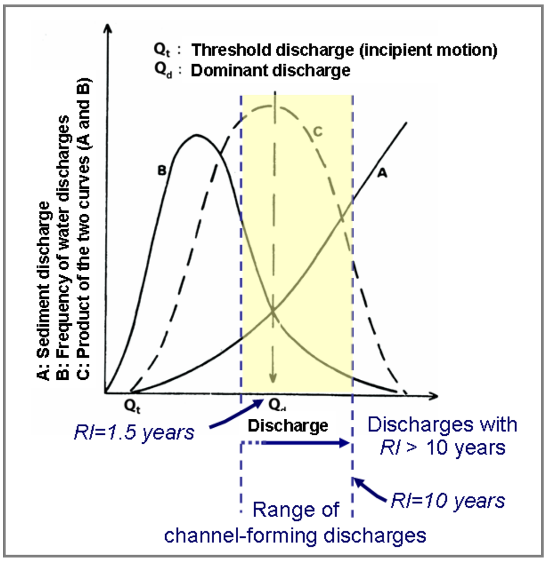



**Figure 46 Range of channel-forming discharges, including the discharges with return interval of up to 10 years. $Q_{1.5}$ (discharge with a return interval of 1.5 years) is the value conventionally assumed as the most representative of channel-forming discharges.**

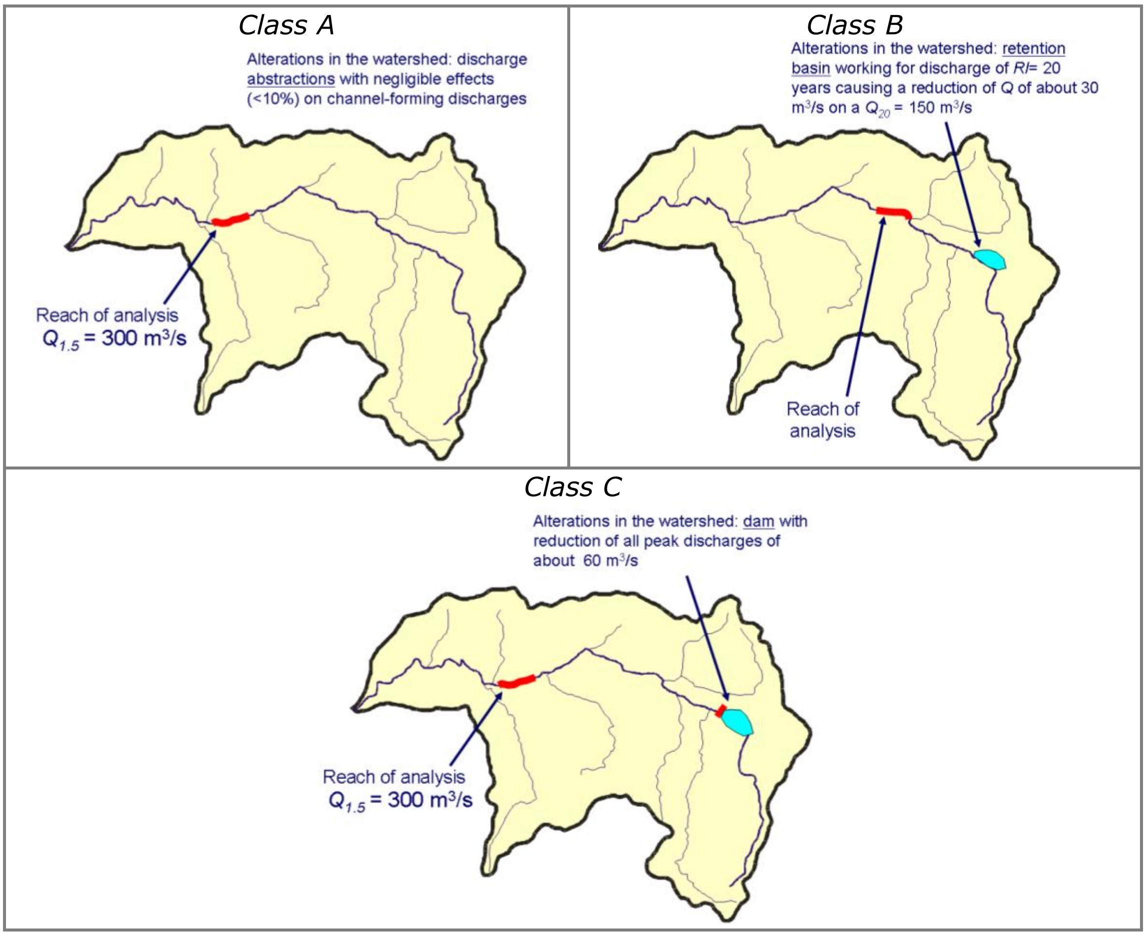



**Figure 47 Upstream alteration of flows. *Class A*: negligible alteration; *Class B*: alteration of high discharges (with *RI* > 10 years) but not of channel-forming discharges; *Class C*: alteration of channel-forming discharges.**

## A2: Upstream alteration of sediment discharges

*Structures in mountain areas*

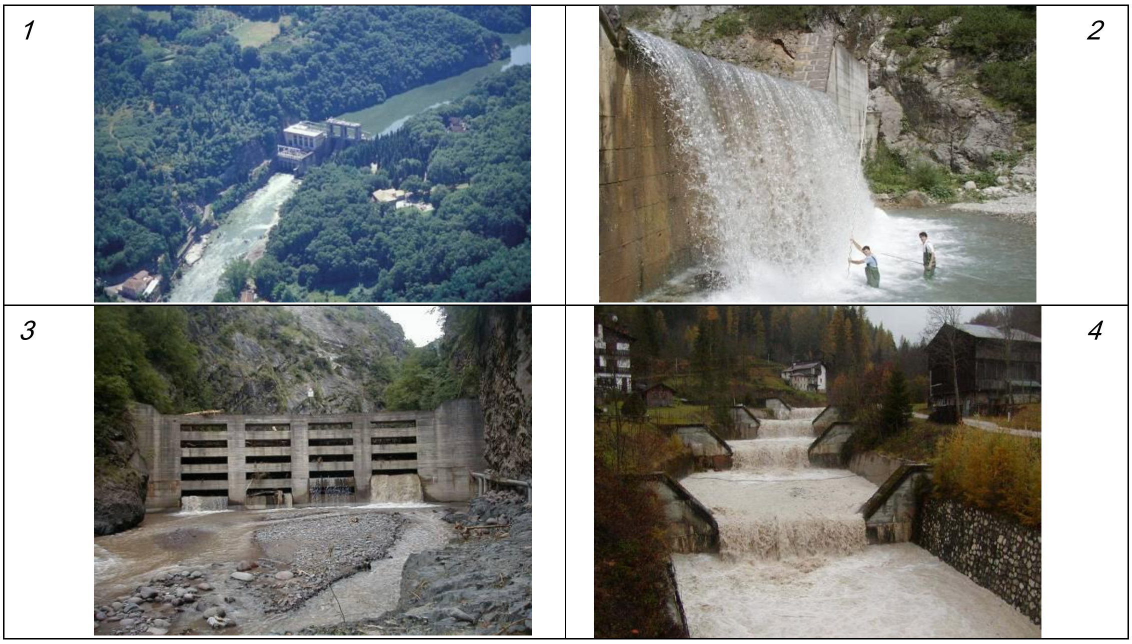



**Figure 48 Transversal structures of alteration of sediment discharges in mountain areas. (1) Dam; (2) retention check dam; (3) open check dam; (4) sequence of stepped consolidation check dams.**

*Structures in hilly – lowland areas*


**Figure 49 Transversal structures of alteration of sediment discharges in hilly and lowland areas. (1) Consolidation check dam; (2) abstraction weir; (3) not filled abstraction weir; (4) filled abstraction weir.**

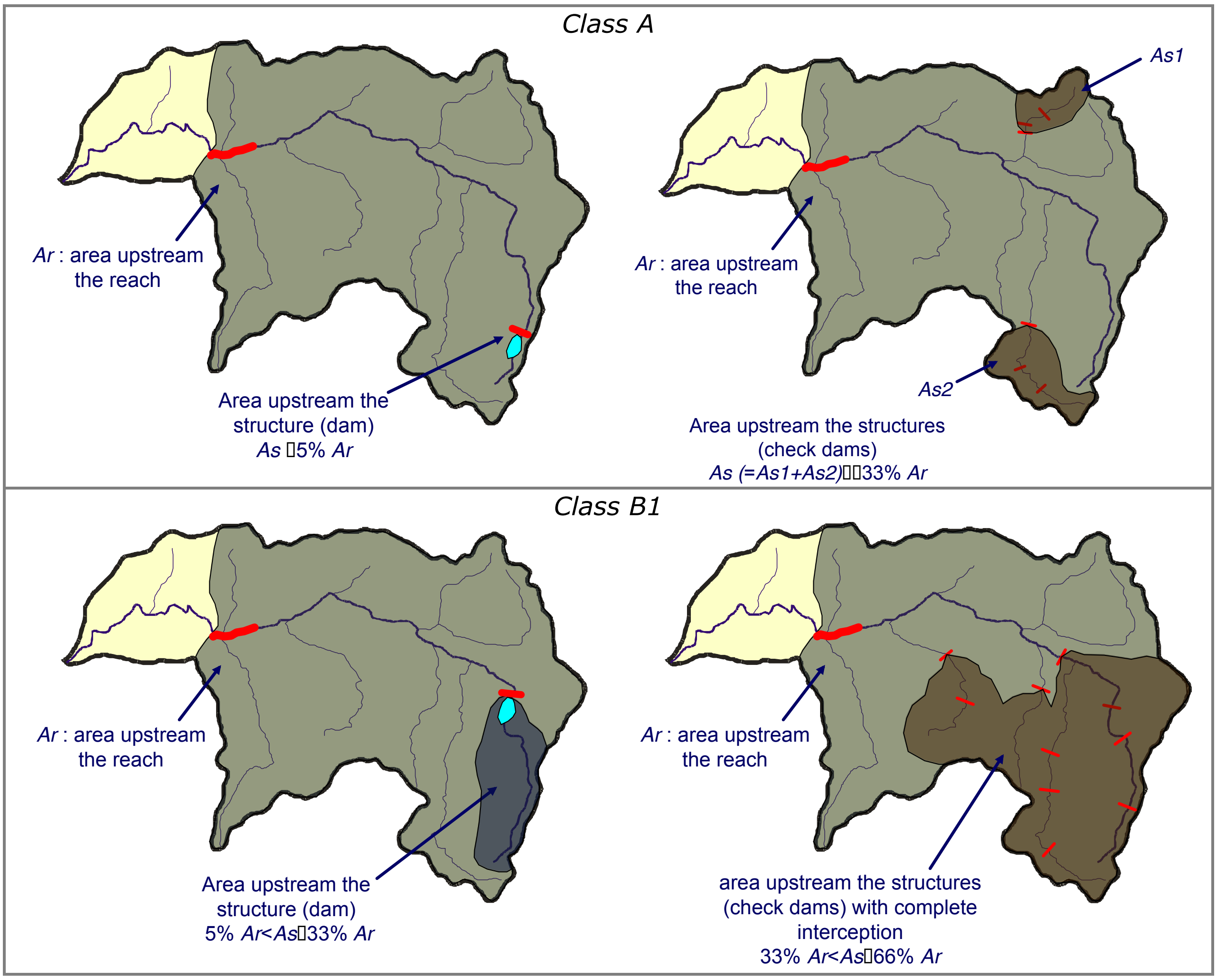



**Figure 50 Upstream alteration of sediment discharges. *Class A*: dam with a negligible drainage area (≤ 5% of the area upstream from the reach, *Ar*) (left); the total area of portions of the watershed with check dams is ≤ 33% of the area upstream from the reach (right). *Class B1*: dam with a drainage area between 5% and 33% of the area upstream from the reach (left); the total area of portions of the watershed with check dams is between 33% and 66% of the area upstream from the reach (it applies in the case of reaches in hilly or lowland areas) (right).**

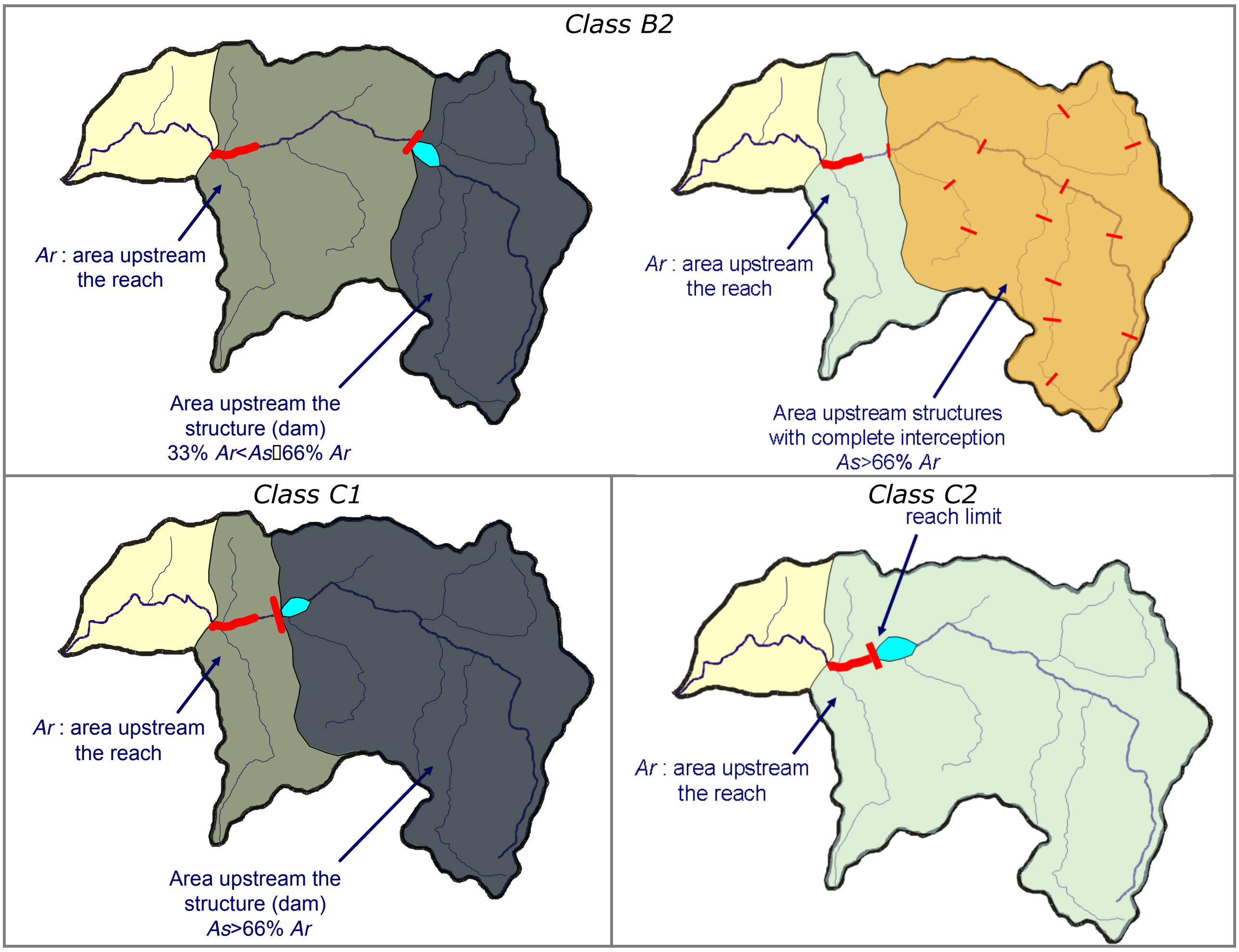



**Figure 50 *(continued)* Upstream alteration of sediment discharges. *Class B2*: dam with a drainage area between 33% and 66% of the area upstream from the reach (left); the total area of portions of the watershed with check dams is > 66% of the area upstream from the reach (it applies in the case of reaches in hilly or lowland areas) (right). *Class C1*: dam with a drainage area > 66% of the area upstream from the reach (left). *Class C2*: dam at the upstream limit of the reach (right).**

## Alteration of longitudinal continuity in the reach

### A3: Alteration of flows in the reach

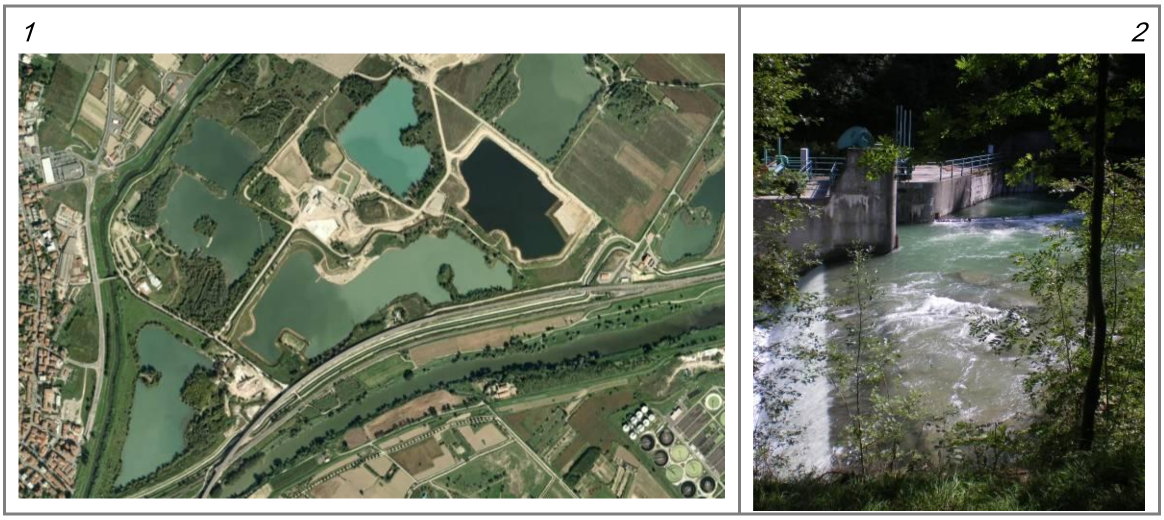



**Figure 51 Other structures (besides those defined for *A1*) that can cause an alteration of flows within a reach. (1) Retention basins; (2) discharge abstraction.**

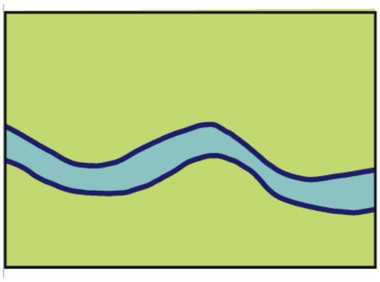
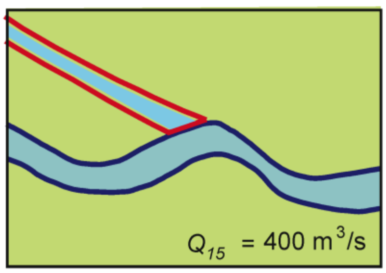
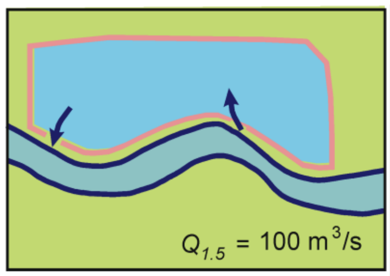
| *Class A* | *Class B* | *Class C* |
|---|---|---|
|  |   |   |
| No alteration | Spillway working only for peak discharges with *RI* > 15 years and causing reduction in *Q* of about 50 m$^3$/s | Retention basin working for all peak discharges (*RI* > 1 year) and causing a reduction in *Q* of about 15 m$^3$/s |

**Figure 52 Alteration of flows in the reach. *Class A*: absence of alteration. *Class B*: alteration of discharges with *RI* > 10 years. *Class C*: alteration of channel-forming discharges.**

## A4: Alteration of sediment discharge in the reach

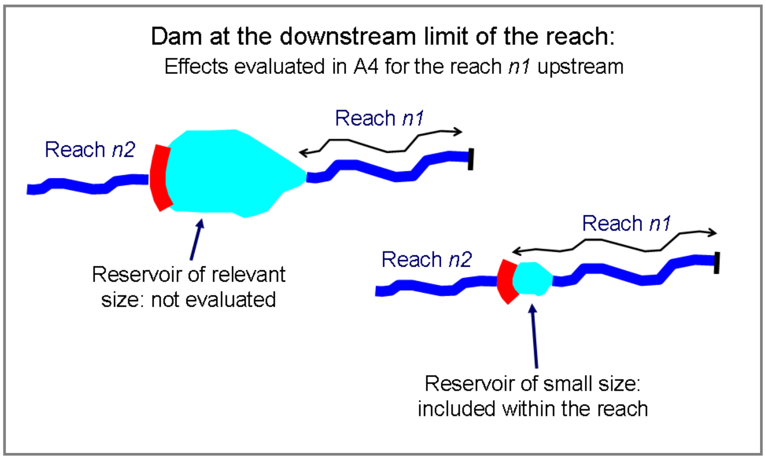



**Figure 53 Rule of evaluation of the effects of a dam and reservoir at the downstream limit of the reach.**

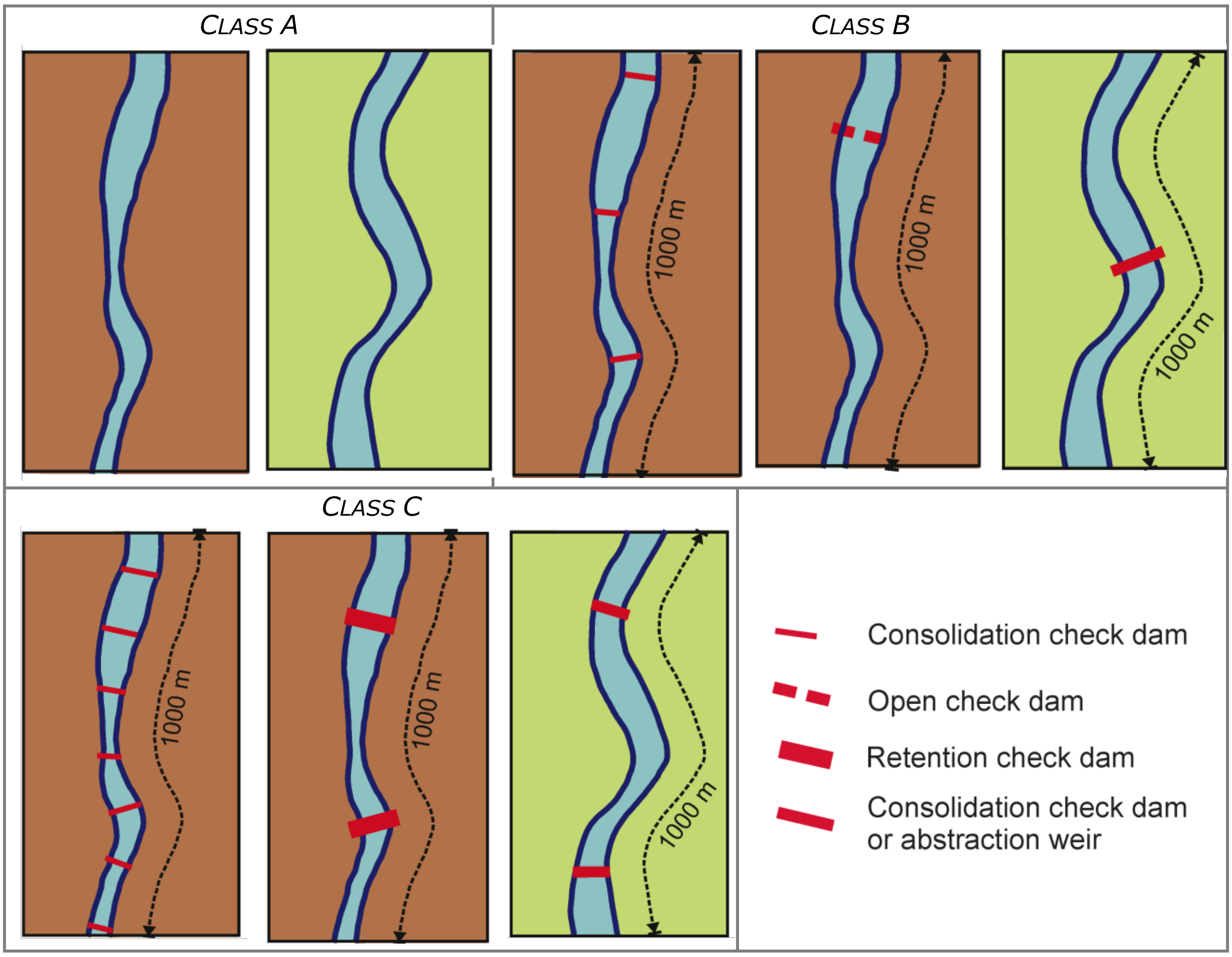



**Figure 54 Alteration of sediment transport. *Class A*: absence of alteration. *Class B* in steep channels (bed slope *S* > 1%): consolidation check dams in limited number (≤ 1 every 200 m); or one or more open check dams. *Class B* in channels with bed slope *S* ≤ 1%: consolidation check dams or abstraction weirs in limited number (≤ 1 every 1000 m). *Class C* in in steep channels (bed slope *S* > 1%): frequent consolidation check dams (> 1 every 200 m) or one or more retention check dams. *Class C* in channels with bed slope *S* ≤ 1%: frequent consolidation check dams and/or abstraction weirs (> 1 every 1000 m).**

1 2

**Figure 55 Cases with very high density of transversal structures: an additional score of 6 or 12 (depending on the density) is applied.**

**A5: Crossing structures**


**Figure 56 Crossing structures. (1) Bridge with interference on fluvial dynamics; (2) crossing structure unrelated to the fluvial corridor; (3) ford with culverts; (4) culvert.**

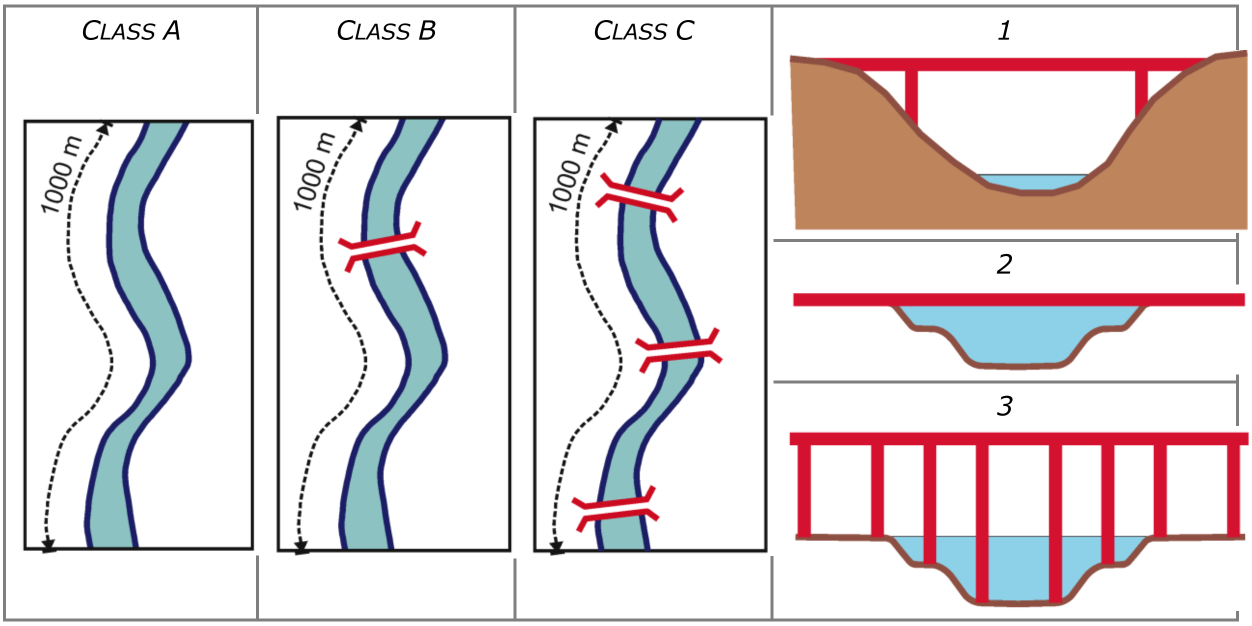



**Figure 57 Crossing structures. *Class A*: absence of structures. *Class B*: crossing structures in limited number (≤1 every 1000 m). *Class C*: frequent crossing structures (>1 every 1000 m). On the right: interference of bridges with the fluvial corridor. (1) Bridge completely unrelated (viaduct crossing a valley at relevant height); (2) bridge with no piers but which may interfere with high discharges; (3) bridge very high but with piers interfering with fluvial dynamics processes.**

## Alteration of lateral continuity

### A6: Bank protections

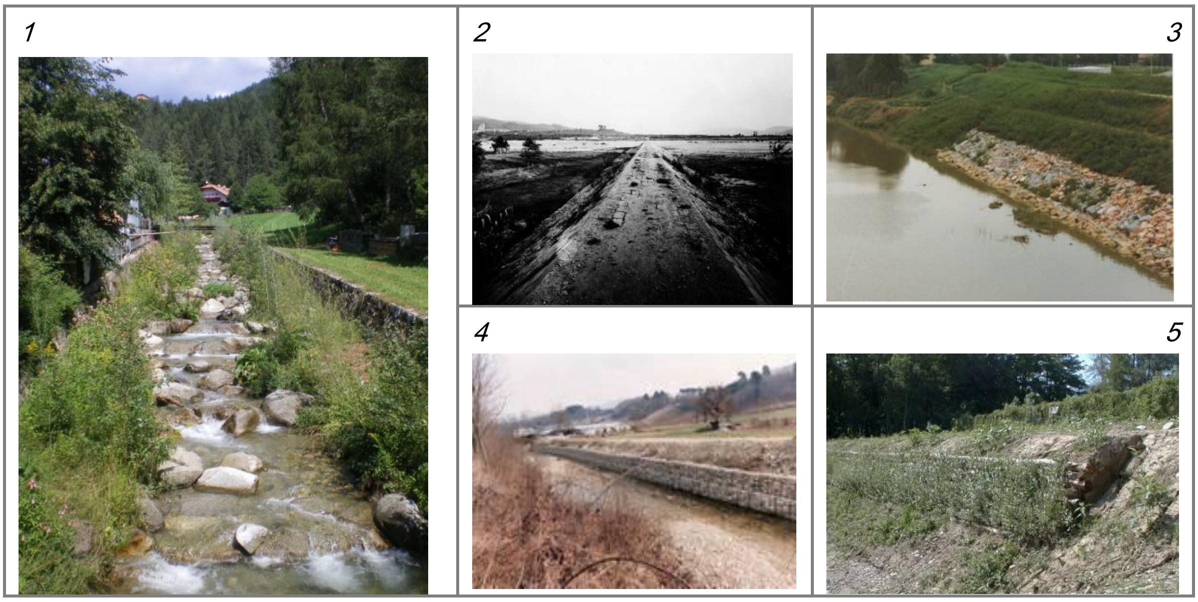



**Figure 58 Bank protections. (1) Bank walls (2) groyne; (3) rip raps; (4) gabions; (5) bioengineering bank stabilization.**

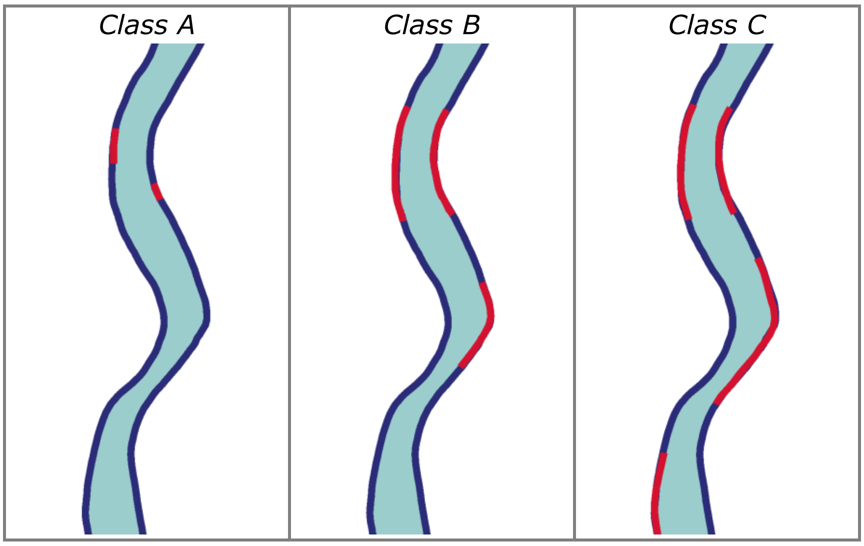



**Figure 59 Bank protections. *Class A*: localized protections (red lines); in the example the structures are 4% of the total length of the two banks. *Class B*: significant presence of bank protections (≤ 33%); in the example they are about 30% of the total length of the two banks. *Class C*: relevant presence of bank protections (> 33%); in the example they occupy about 50% of the total length of the two banks.**

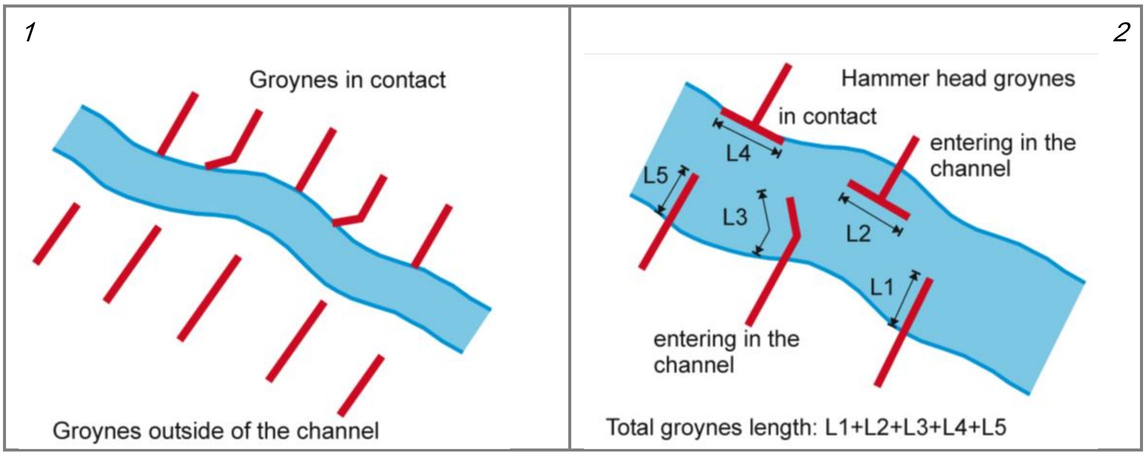



**Figure 60 Case of groynes. (1) Groynes outside of the channel are not considered (instead, they are accounted for in the indicator *F5*); in the case of straight groynes in contact with the channel boundary, the width of the groyne head is usually negligible. (2) In the case of groynes entering in the channel, the greater size between protruding length and head width is considered (the latter is generally the prevailing size in the case of hammer head groynes). Note that hammer head groynes in contact (as opposed to straight or bayonet groynes) are considered.**

## A7: Artificial levées

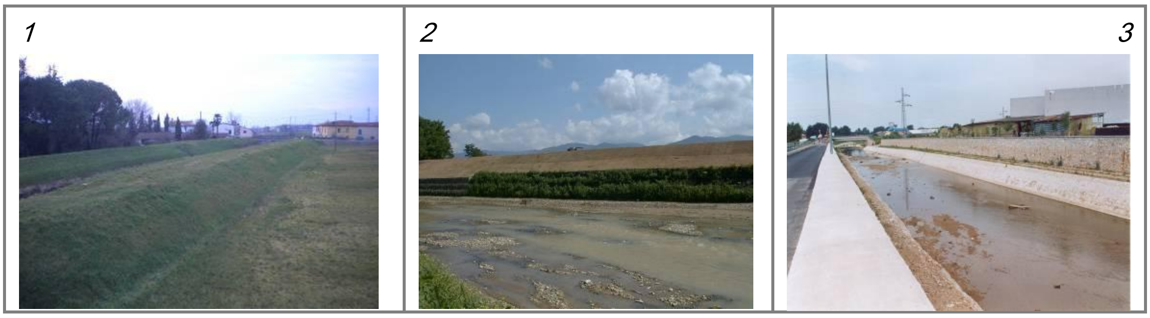



**Figure 61 Artificial levées. (1) Earth levees; (2) bank-edge levee; (3) bank walls with function of levees.**

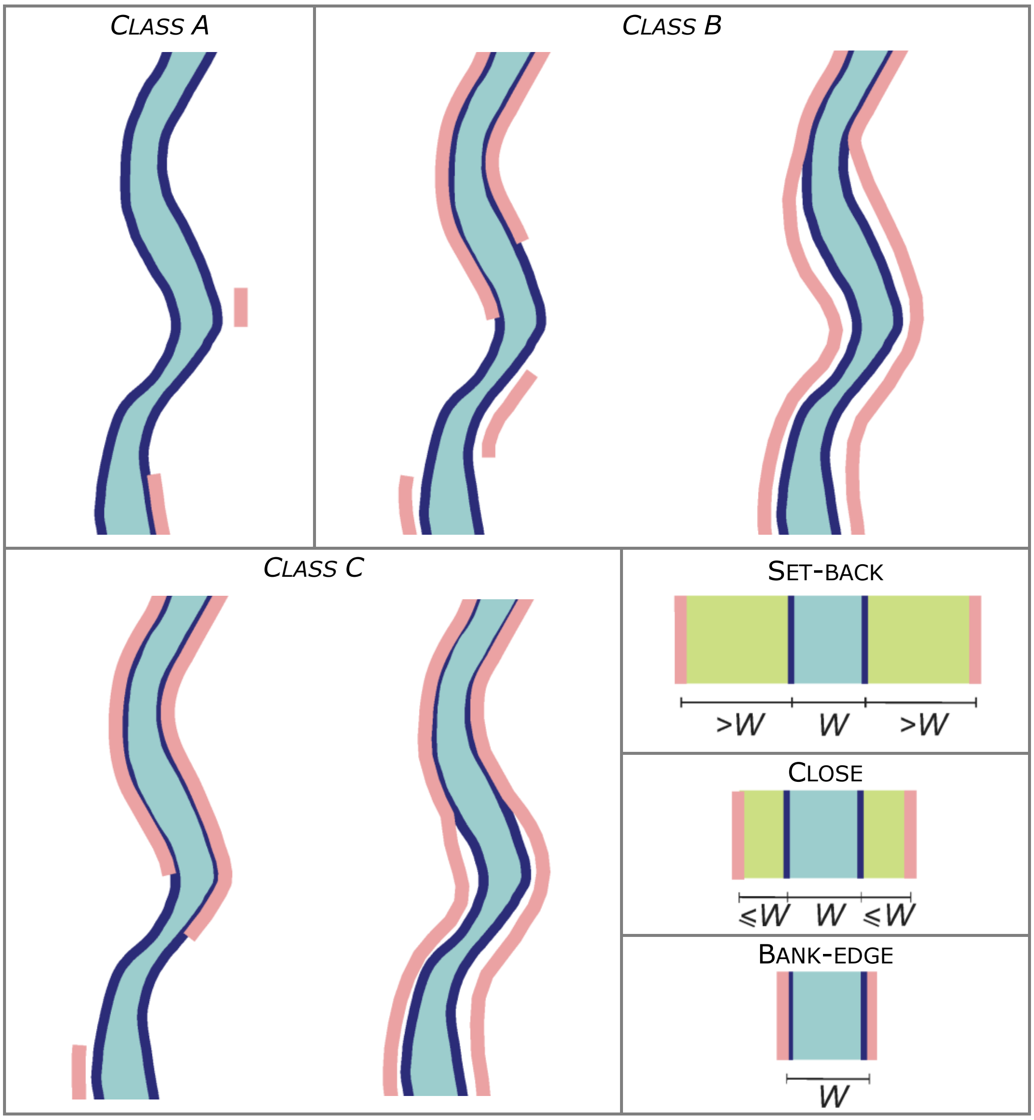



**Figure 62 Artificial levees. *Class A*: localized bank-edge or close levees (< 10%). *Class B*: the total sum of bank-edge and close levees is < 90%, with bank-edge are between 33% and 50% (left), or the total sum of bank-edge and close levees is > 90% but bank-edge are < 33% (right). *Class C*: bank-edge levees are > 50% of the reach (left), or bank-edge levees are between 33% and 50% but the total sum of bank-edge and close levees is > 90% (right). Bottom right: definition of set-back, close and bank-edge levees.**

**Figure 63 Cases of bank-edge levées occurring for most of the reach, for which an <u>additional score of 6 or 12</u> (depending on the % of the reach length) is added.**

Alteration of channel morphology and/or substrate

## A8: Artificial changes of river course

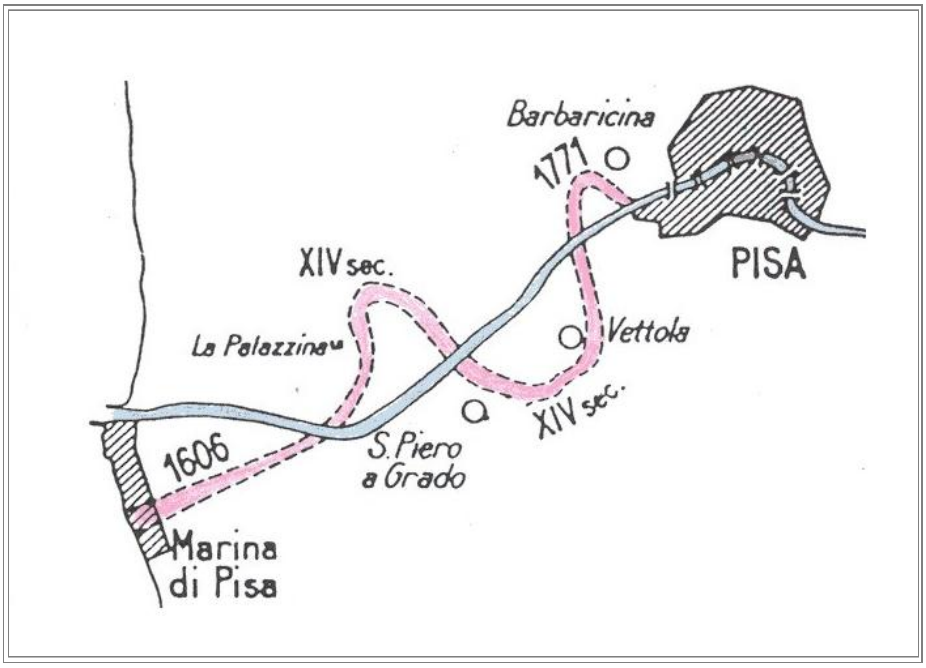



**Figure 64 Artificial changes of river course. Example of well known artificial changes (meander cut-offs, change of position of river mouth) occurring in historical times.**

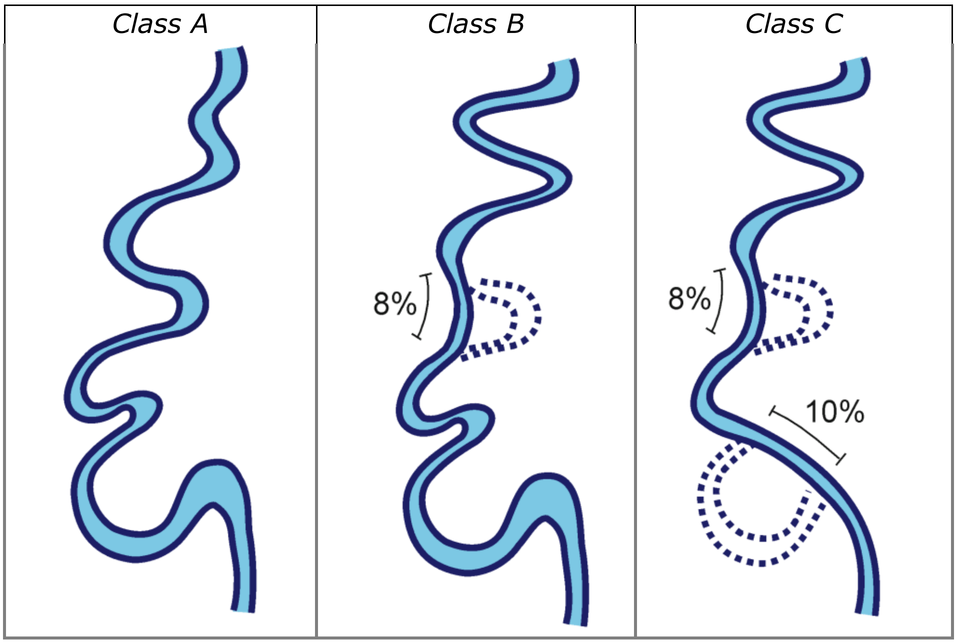



**Figure 65 Artificial changes of river course. *Class A*: absence of artificial changes. *Class B*: artificial changes for a length < 10% of the reach. *Class C*: artificial changes for a length > 10% of the reach.**

## A9: Other bed stabilization structures

| | |
|---|---|
| *Class A*  | *Class B*  |
| *Class B*  | *Class C1*  |
| *Class C2*  |  |

**Figure 66  Other bed stabilization structures and revetments. *Class A*: total absence of other bed stabilization structures or revetments. *Class B*: presence of sills (first row on right) or mass ramps (second row on left) with low density. *Class C1*: various sills and partial bed revetment. *Class C2*: total bed revetment with impermeable systems.**

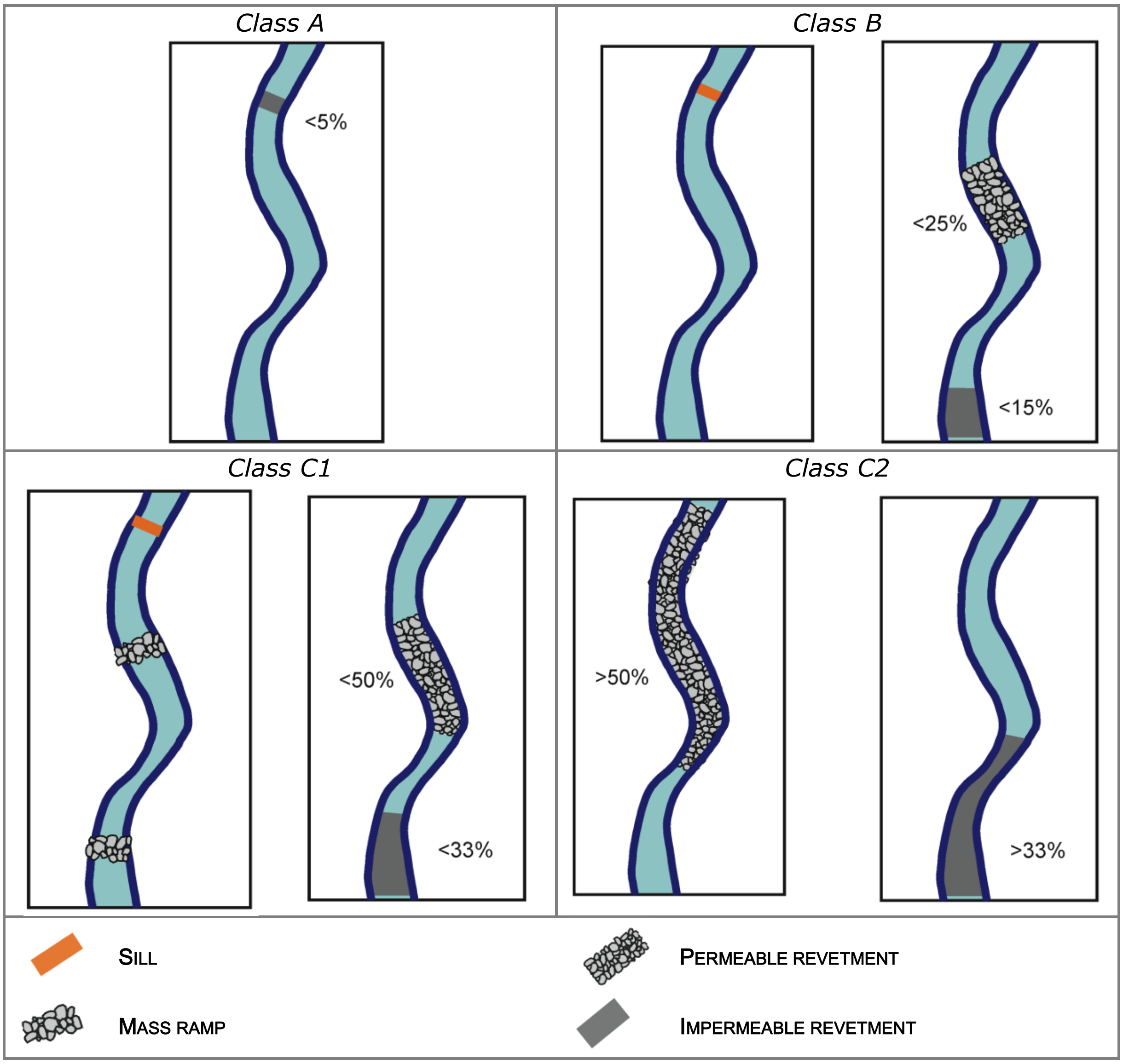



**Figure 67 Other bed stabilization structures and/or revetments. *Class A*: absence of other structures and localized revetments (<5%). *Class B*: bed stabilization structures (sills, ramps) with a density ≤ 1 every *n* (*n* = 200 m for steep channels, *n* = 1000 m for bed slope S≤1%), or permeable revetments with length ≤ 25% of the reach and/or impermeable revetments with length ≤ 15% of the reach. *Class C1*: : bed stabilization structures (sills, ramps) with a density > 1 every *n*, or permeable revetments with a length ≤ 50% of the reach and/or impermeable revetments ≤ 33% of the reach. *Class C2*: permeable revetments > 50% of the reach and/or impermeable revetments > 33% of the reach.**

## Interventions of maintenance and removal

### A10: Sediment removal


**Figure 68 Sediment removal. (1) and (2) Recent and current activity; (3) and (4) indirect indicators of past activity are the presence of mining sites. In the case of partly- and unconfined channels, *Class B1, B2* or *C* depends on the occurrence of sediment removal in the past (since 1950's) and/or in recent times (last 20 years).**

## A11: Wood removal


**Figure 69 Wood removal. *Class A*: absence of interventions of wood removal. *Class B*: partial removal, including removal by private citizens. *Class C*: total removal by public agencies.**

## A12: Vegetation management


**Figure 70 Vegetation management. *Class A*: absence of vegetation cutting interventions. *Class B*: interventions of selective cutting. *Class C*: interventions of total vegetation cutting along most of the reach. Management of emergent aquatic macrophytes is also evaluated in the indicator *A12*, but only in the case of low-energy sinuous, meandering or anabranching channels (see *Guide for Compilation of the Evaluation Forms* for details).**

## *Channel adjustments*

### CA1: Adjustments in channel pattern

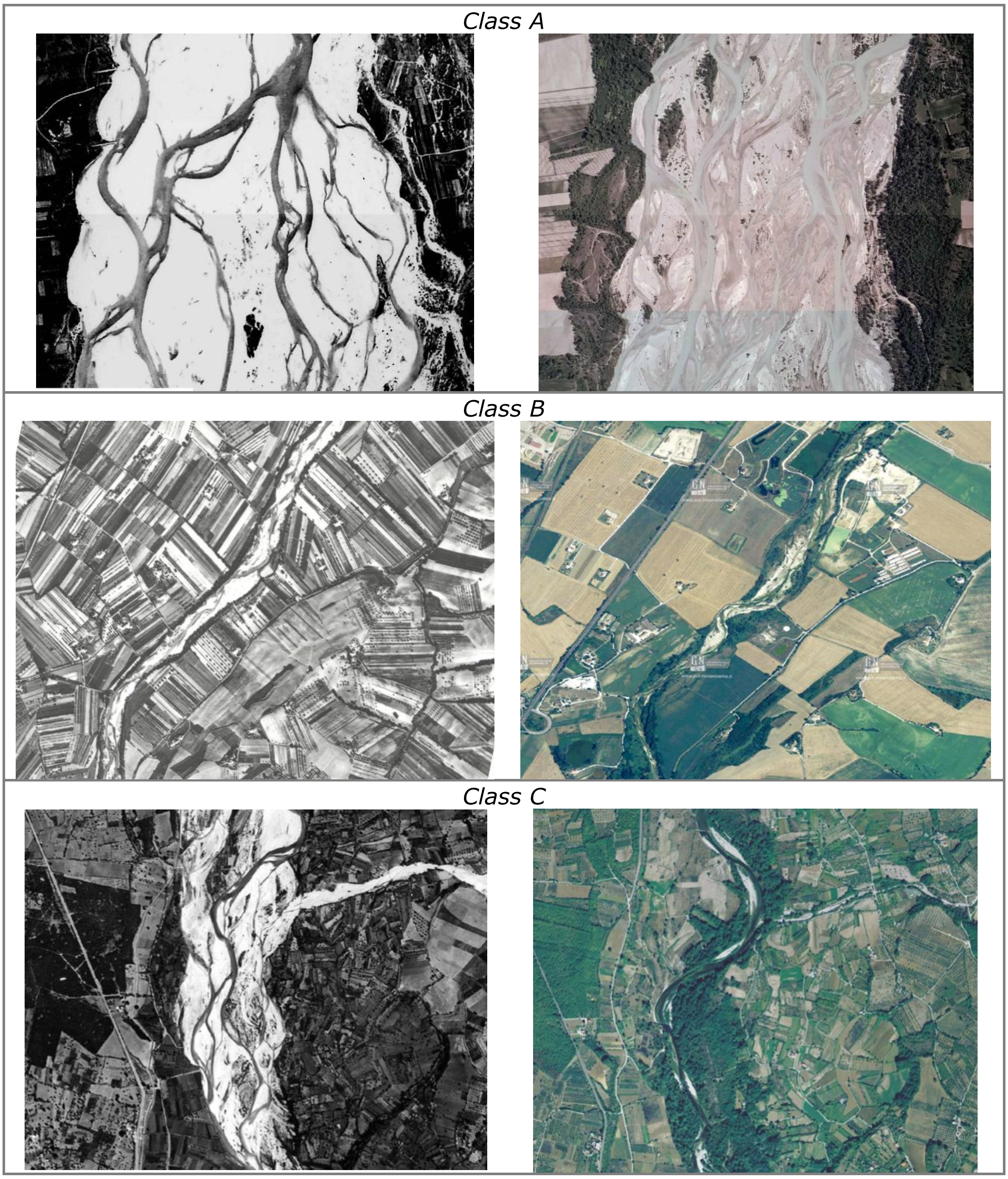



**Figure 71 Adjustments in channel pattern (on the left aerial photo dated 1954, on the right the current situation). *Class A*: the channel maintains a prevailing braided pattern, although channel narrowing occurred. *Class B*: change from wandering to sinuous. *Class C*: change from braided to sinuous.**

## CA2: Adjustments in channel width


**Figure 72 Adjustments in channel width (on the left aerial photo dated 1954, on the right the current situation). *Class A*: very limited channel narrowing (< 15%). *Class B*: channel narrowing from 15% to 35% of channel width in 1930s-60s. *Class C*: very intense channel narrowing (> 35%).**

## CA3: Bed-level adjustments

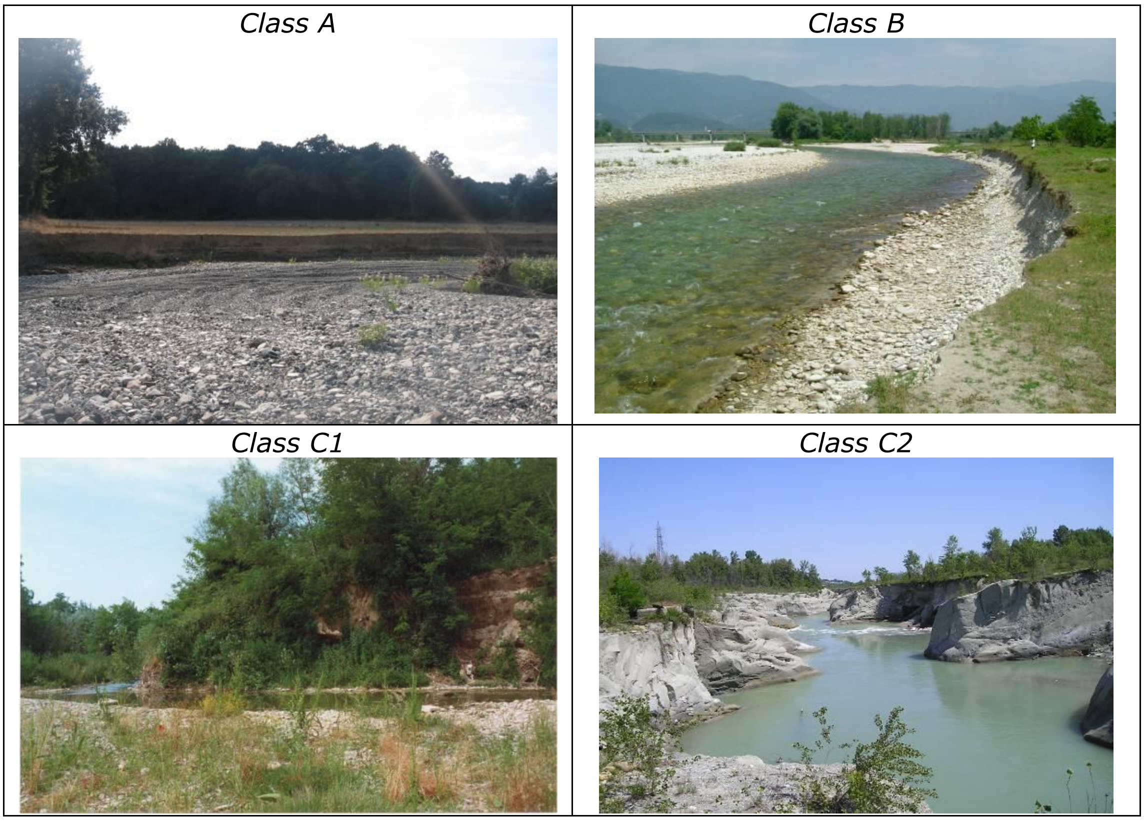



**Figure 73 Bed-level changes. *Class A*: negligible incision (< 0.5 m). *Class B*: incision from limited to moderate (from 0.5 to 3 m). *Class C1*: intense incision (> 3 m). *Class C2*: very intense incision (> 6 m) causing the complete erosion of the alluvial deposits.**

<u>Field evidence</u>

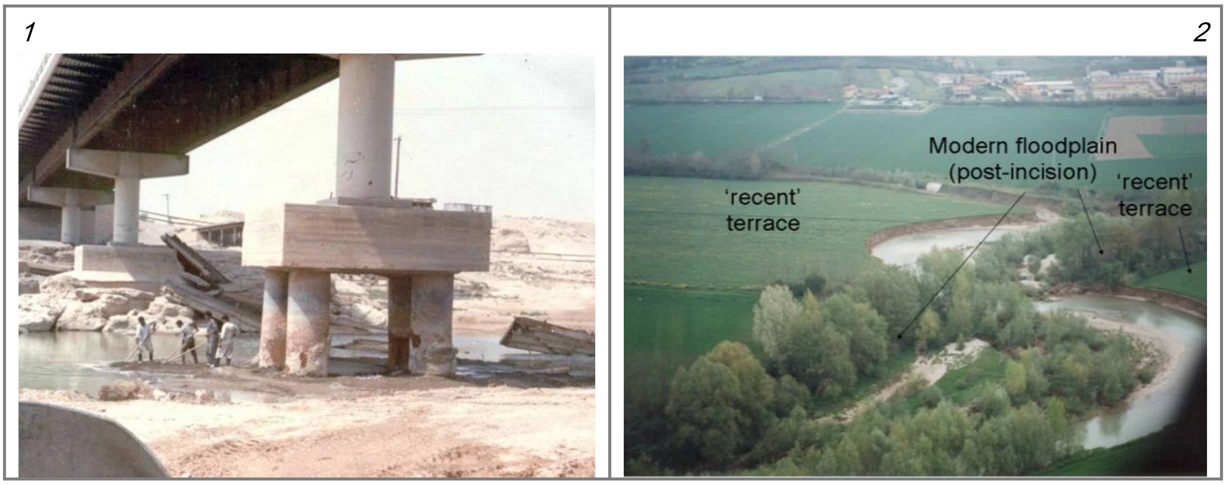



**Figure 74 Field evidence of incision. (1) Exposed bridge piers. (2) Differences in level between modern (post – incision) floodplain and recent terrace (the latter corresponding to the pre – incision floodplain).**

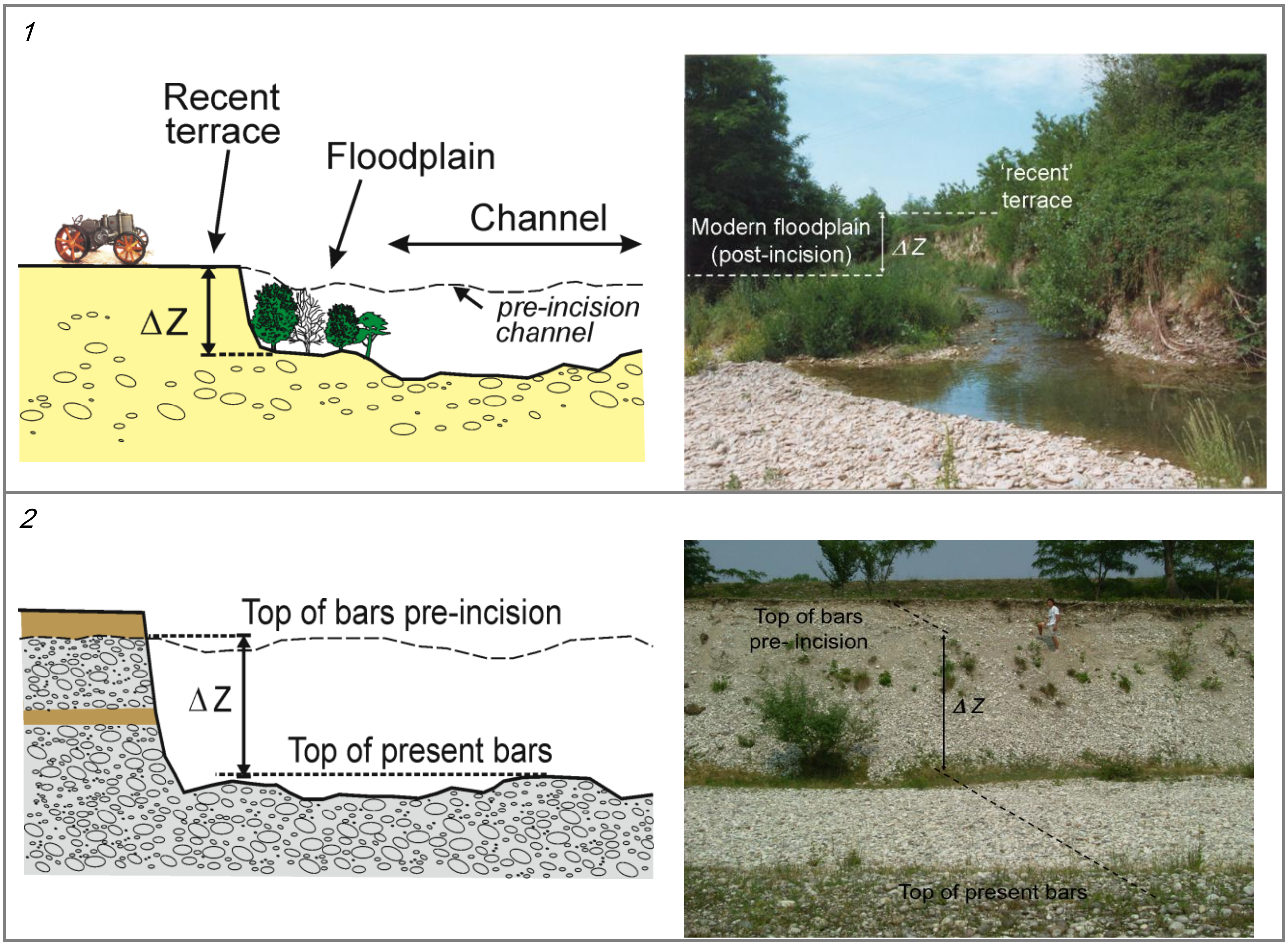



**Figure 75 Estimation of the amount of incision based on differences in elevation among surfaces. (1) Measurement of difference in elevation (ΔZ) between modern floodplain and recent terrace (pre- incision floodplain); (2) measurement of difference in elevation between the top of gravel on an eroding bank (corresponding to the top of bars before incision) and top of present channel bars.**