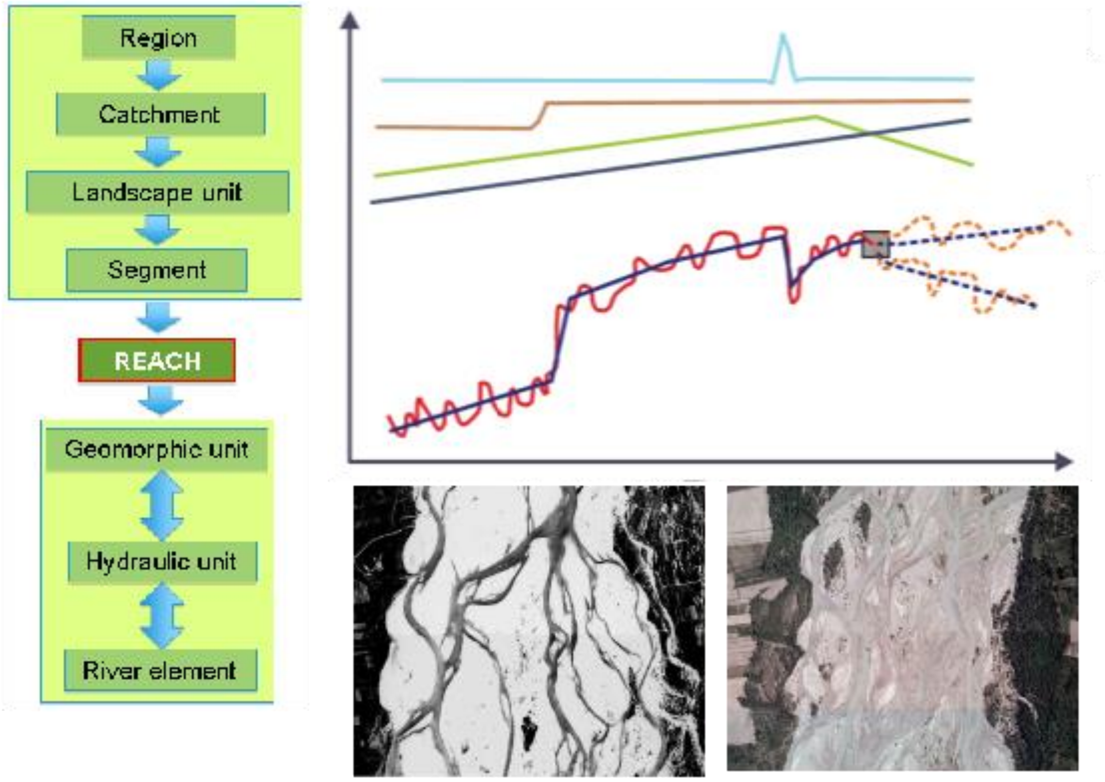
THEME: Environment (including climate change)
TOPIC: ENV.2011.2.1.2-1 Hydromorphology and ecological objectives of WFD
Collaborative project (large-scale integrating project)
Grant Agreement 282656
Duration: November 1, 2011 – October 31, 2015

REFORM

REstoring rivers FOR effective catchment Management



Deliverable	D6.2 Part 1
Title	Final report on methods, models, tools to assess the hydromorphology of rivers
Authors	(authors of D6.2 Part 1*)

M. Rinaldi[1], A.M. Gurnell[2], B. Belletti[1], M.I. Berga Cano[3], S. Bizzi[4], M. Bussettini[5], M. Gonzalez del Tanago[6], R. Grabowski[2], H. Habersack[7], M. Klösch[7], F. Magdaleno Mas[3], E. Mosselman[8], M. Toro Velasco[3], P.Vezza[9]
[1]UNIFI, [2]QMUL, [3]CEDEX, [4]JRC, [5]ISPRA, [6]UPM, [7]BOKU, [8]Deltares, [9]Politecnico di Torino (voluntary contribution)

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 1 of Deliverable 6.2 as follows:
M. Rinaldi, A.M. Gurnell, B. Belletti, M.I. Berga Cano, S. Bizzi, M. Bussettini, M. Gonzalez del Tanago, R. Grabowski, H. Habersack, M. Klösch, F. Magdaleno Mas, E. Mosselman, M. Toro Velasco, P. Vezza (2015) Final report on methods, models, tools to assess the hydromorphology of rivers, Deliverable 6.2, 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.

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 (this volume) provides an overall framework for hydromorphological assessment. Part 2 includes thematic annexes on protocols for monitoring indicators and models. Part 3 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 several case studies of several tools and methods reported in the previous parts.

Summary of Deliverable 6.2 Part 1

Objective

The aim of this Deliverable is to provide a flexible, open-ended framework of procedures and tools through which practitioners can summarise river conditions, set monitoring activities, support the selection of appropriate and sustainable restoration actions.

Methods and Results

The overall assessment framework presented in this Deliverable is a more prescriptive version of the open-ended REFORM hydromorphological framework developed in Deliverable 2.1. Therefore, it provides a more formal set of methods and tools with which to practically assess and monitor hydromorphological conditions.

Some of the key features of the REFORM hydromorphological framework presented here are the following: (i) it provides a flexible set of procedures such that member states can incorporate their own data sets and methods; (ii) it is organised in a sequence of stages, each one containing a series of procedural steps that support the assessment of river conditions in a consistent manner; (iii) its application allows representative reaches or sites to be selected for monitoring river conditions, and for appropriate upscaling or downscaling of information; (iv) it can be used to classify and understand current conditions, to assess the potential for morphological changes, and to support prioritisation of actions and selection of sustainable management strategies.

This report (D6.2 Part 1) describes the succession of logical stages required to implement the framework and its assessments as follows.

(1) Catchment-wide delineation and spatial characterization of the fluvial system. This phase provides a delineation, characterization and analysis of the river system in its current conditions, according to the framework developed in D2.1.

The main outputs are: (i) delineation of spatial units; (ii) characterization of spatial units, including hydrological characteristics, sediment sources and delivery, characteristics of the river and its corridor, typical assemblages of geomorphic units; (iii) synthesis of the main physical pressures and impacts at catchment scale; (iv) spatial patterns of the main morphological parameters and their control on channel morphology.

(2) Assessment of temporal changes and current conditions. This phase involves reconstructing the history and evolutionary trajectories of morphological changes and assessing river conditions in its present state.
The main outputs are: (i) natural and human factors influencing the different spatial units in historical times; (ii) evolutionary trajectories of channel changes; (iv) GIS mapping synthesizing pressures and critical reaches at catchment scale; (v) hydrological, morphological and riparian vegetation state (‘river condition assessment’); (vi) geomorphic units existing along the investigated reaches; (vii) identification of the problems and the most critical reaches at catchment scale; (viii) reports on monitored parameters or indicators and their temporal changes.

(3) Assessment of scenario-based future trends. This phase is aimed to identify possible scenarios of hydromorphological modification.
The main outputs are: (i) mapping of sensitivity and morphological potential at catchment scale; (ii) synthesis of past channel evolution, current conditions, and possible future trends.

(4) Identification of management actions. This last phase is aimed to identify possible hydromorphological restoration or management actions, and strongly interacts with the identification of restoration potential and strategies developed in REFORM WP5.
Each stage contains a series of procedural steps that are followed to conduct an assessment of river conditions and lastly to support the selection of appropriate management actions in a meaningful, coherent, and consistent manner.
The main outputs are: (i) definition of one or more scenarios of management actions or restoration interventions; (ii) potential effects of proposed interventions on physical processes and overall hydromorphological conditions.

The methods and tools developed or revised in this Deliverable have relevance for hydromorphological assessment and monitoring aimed at implementing the WFD. Concerning the definition of WFD water bodies, the REFORM framework uses a more standard geomorphological terminology for the spatial units and the procedures recommended include a more comprehensive and explicitly process-based set of criteria. Application of the REFORM framework to delineate segments often generates boundaries that correspond to WFD water body boundaries, which can be further subdivided into ‘reaches’ using additional geomorphological criteria such as the classification of river typologies.
This Deliverable also suggests suitable methods for the evaluation of the different components of an overall ‘river condition assessment’, such as for hydrological assessment (IARI, IAHRIS), morphological assessment (MQI, Rivers-MImAS, SYRAH), and riparian vegetation assessment (RQI). Specifically, the Morphological Quality Index (MQI) has been extended and tested during the project and is the recommended method from REFORM for the assessment of morphological conditions.

Conclusions and recommendations

In order to characterise, assess, and monitor hydromorphological conditions of rivers, an overall analysis of different components (hydrology, morphology, riparian vegetation) is required. The analysis must be based on appropriate spatial and temporal scales.

For sustainable solutions to river management problems, it is crucial to develop understanding of the functioning of a river reach in the context of the character and changes in the spatial units (segment, landscape unit, catchment, biogeographical region) within which the reach is located.

Knowledge of past hydromorphological changes which have occurred at different spatial scales, their causes, and reconstruction of the river evolutionary trajectory in response to those changes is a fundamental component of the analysis.

We provide the following *key recommendations* for stakeholders:

- We recommend using two linked process-based approaches to achieve a comprehensive and synergic hydromorphological assessment: (i) a multi-scale, open-ended framework to develop an understanding of river reach hydromorphology; (ii) a more prescriptive approach based on the integration of more specific assessment tools.
- The delineation of WFD water body boundaries can be integrated into the REFORM framework at the segment scale, and then the water bodies can be further sub-divided into 'reaches' using additional geomorphological criteria such as the identification of river (morphological) types.
- The Morphological Quality Index (MQI) is recommended to assess river conditions, i.e. for analysing and interpreting critical problems and causes of alteration. The method should be implemented for the entire gradient of morphological conditions (not only for high status water bodies) for supporting interpretation of BQEs, and should be integrated with a characterization of the assemblage of geomorphic units (GUS) that determine the morphology at reach scale.

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

List of Topics covered in D6.2 Parts 2, 3, 4, and 5

D6.2 Part 2: Thematic Annexes on monitoring indicators and models
A Hydrological monitoring indicators
B. Morphological monitoring indicators
C. Riparian vegetation monitoring indicators
D. Hydromorphological models

D6.2 Part 3: Guidebook for the evaluation of stream morphological conditions by the Morphological Quality Index (MQI)

D6.2 Part 4: The Geomorphic Units survey and classification System (*GUS*)

D6.2 Part 5: Applications

1. Introduction

This Deliverable is the main output of the activities carried out in Tasks 6.1, 6.2 and 6.3 of Work Package 6 of the REFORM project. It is organised in the form of a methodological framework, structured in stages and steps reflecting the logical sequence of analysis that should be undertaken.

Some of the activities carried out in Tasks 6.1, 6.2 and 6.3 are also reported in other deliverables (e.g., D6.3). In particular, note that ecological monitoring indicators are not included in this Deliverable, as they are widely reported in other Work Packages (e.g., WP3) and summarised in the Wiki and in Deliverable 6.3.

1.1 The Aims of Tasks 6.1, 6.2 and 6.3 of REFORM WP6

This report and its annexes summarize the outputs from Tasks 6.1, 6.2, and 6.3. As described in the original proposal, the aims of these tasks were as follows:

Task 6.1: Selection of indicators for cost-effective monitoring and development of monitoring protocols to assess river degradation and restoration

This task selects and identifies key indicators from the candidate indicators developed in previous WPs, encompassing the impacts of pressures and the benefits of measures on the ecological status and ecosystem services of rivers and floodplains. The indicators will have a close link to particular hydromorphological conditions. For each indicator a protocol for cost-effective monitoring will be made to support monitoring programmes for the WFD, GWD and river restoration projects. The preliminary selection of indicators in this task will be tested and validated on the case studies within WP4.

- Selection of indicators (hydrological, morphological, ecological and indicators for river ecosystem goods and services) sensitive to changes in hydromorphology i.e. both degradation and recovery through restoration.
- Deriving improved single metrics with higher sensitivity towards hydromorphological change as well as multi-metrics that are sensitive to multiple pressures.
- Development of web-based guidelines with protocols to cost-effectively monitor the selected indicators.

Task 6.2: Improve existing methods to survey and assess the hydromorphology of river ecosystems

This task produces a cost-effective and widely applicable system for channel - floodplain hydromorphological survey, assessment and classification, with specific consideration to channel dynamics and floodplains, and practical suitable for the WFD and consistent with CEN (2002) standards. The method progresses beyond the state-of-the-art as it gives insight into hydrological and morphological patterns and processes at various scales with links to the ecological status. The task is complementary to task 6.1, which provides selected indicators, and will build on results of WP 2, 3 and 4.

- Improvement and expansion of a process-based method, recently developed in Italy (Rinaldi et al. 2010), that can be applied across Europe, by defining a scoring system based on key hydromorphological indicators that are ecologically relevant.
- The draft method will be applied and tested within WP4 and using existing data from a selected number of case studies across a representative range of European streams, in terms of: (i) catchment and natural channel typology; (ii) types and degree of human alterations and consequent channel adjustments.

Task 6.3: Identification and selection of existing hydromorphological and ecological models and tools suitable to plan and evaluate river restoration

This task builds on the results of task 1.1 and aims to produce a guideline for the use mathematical models and other quantitative tools by scientists and consultants supporting stakeholders and practitioners to assess rivers and their restoration. Furthermore, applications and experiences of models used in other WPs (i.e. WP4) are summarized in this task to advice on their applicability in river restoration projects.

- Development of guidelines and recommendations on possible use of mathematical models and other tools to solve specific problems related to river assessment and restoration, and definition of criteria for the use of more advanced numerical models in assessing effectiveness, impacts and sustainability of hydromorphological complex restoration approaches.

1.2 Contents of this Report in Relation to the Originally Proposed Work

As described in the original proposal, the report contains: (1) guidelines containing criteria for the use of mathematical models and tools; (2) factsheets and monitoring protocols for indicators detecting hydromorphological change when assessing ecological status of rivers and floodplains; (3) improved methods for hydromorphological survey.

The overall methodological structure of the assessment of hydromorphological conditions stems from the multi-scale framework developed in REFORM Deliverable 2.1 and partly builds on existing geomorphological approaches (e.g., Brierley and Fryirs, 2005; Rinaldi et al., 2015). However, the overall assessment framework presented in this Deliverable is a more prescriptive version of the open-ended REFORM hydromorphological framework developed in Deliverable 2.1. Therefore, it provides a more formal set of methods and tools with which to practically assess and monitor hydromorphological conditions.here the framework is presented in a more formal way. In particular:
(1) The framework provides a structure, organized in stages and steps that are consistent with Deliverable D2.1, on how to assess and monitor hydromorphological conditions.
(2) The deliverable emphasizes the practical application of assessment and monitoring tools for the implementation of the WFD, including both existing and newly developed methods and tools that fit within this framework.

The overall framework is described in this main report, which is composed of six chapters. Some thematic aspects, methods, and applications are further elaborated in a series of annexes.

The main report is organised in the following chapters:
1. Introduction
2. The Overall Methodological Framework
3. Stage I: Catchment-wide Delineation and Spatial Characterization of the Fluvial System
4. Stage II: Assessment of Temporal Changes and Current Conditions
5. Stage III: Assessment of Scenario-Based Future Trends
6. Stage IV: Management

The first volume of annexes (Part 2) focuses on methods for monitoring indicators and related models, and comprises the following parts:
A. Hydrological monitoring indicators
B. Morphological monitoring indicators
C. Riparian vegetation monitoring indicators
D. Hydromorphological models

The second annex (Part 3) is a Guidebook for the evaluation of stream morphological conditions by the Morphological Quality Index (MQI), and comprises the following parts:

1. The Morphological Quality Index (MQI)
2. The Morphological Quality Index for monitoring (MQIm)

Appendix 1: Evaluation Form for Confined Channels
Appendix 2: Evaluation Form for Partly Confined or unconfined Channels
Appendix 3: Guide to the Compilation of the Evaluation Forms
Appendix 4: Illustrated Guide to the Compilation of the Evaluation Forms

The third volume of annexes (Part 4) describes the Geomorphic Units survey and classification System (GUS), and is composed by the following parts:

A. The Geomorphic Units survey and classification System (GUS)
B. Guide to the application of the GUS

Appendix 1: Survey and classification forms
Appendix 2: Geomorphic units and macro-units list
Appendix 3: Glossary

The last annex (Part 5) presents the following applications of some of the methods or components of the overall framework:

1. Applications of MQI and MQIm to European case studies
2. Application of remote sensing data for hydromorphological characterization
3. The Hydromorphological Evaluation Tool (HYMET).

IMPORTANT NOTE: The methods and tools included in this framework and used to assess hydromorphological conditions are drawn from the disciplines of hydrology, geomorphology, and riparian-floodplain vegetation dynamics. Therefore, the participation of a trained hydrologist/geomorphologist in the application of the methodology is essential if misinterpretations are to be avoided. Furthermore, although secondary sources provide much of the required information, data acquisition and checking by field survey is strongly recommended. Application of the framework without the necessary skills and field survey could seriously limit the validity of its application.

2. The Overall Methodological Framework

The overall methodological framework provides a coherent set of methods and tools with which to practically assess and monitor hydromorphological conditions. The framework is structured into a sequence of procedural stages and steps in order to assess river conditions and to support the selection of appropriate management actions.

The spatial and temporal contexts are based on the multiscale, process-based, hierarchical framework developed in D2.1 (Gurnell et al., 2014).

The overall framework incorporates four stages: (1) delineation and characterization of the river system; (2) assessment of past temporal changes and current river conditions; (3) assessment of future trends; (4) identification of management actions.

2.1 The Spatio-Temporal Context

This section briefly reviews some of the key concepts that underpin the methodology. The assessment of hydromorphological conditions requires that a given river reach must be placed in an appropriate spatial and temporal context, understanding connectivity of physical processes between different spatial units, their temporal evolution, and causes of change.

Concerning the spatial context of analysis, a multiscale hierarchical approach is fundamental for many management applications, for example for selecting sampling and monitoring sites, and interpreting and extrapolating information gathered at specific sites to other similar sites (Brierley et al., 2013). The multi-scale hierarchical approach developed in Gurnell et al. (2014) (Figure 2.1) provides the spatial framework for assessment described in this deliverable.

The temporal context of the framework is also developed from D2.1 and recognises that fluvial systems are dynamic and follow a complex evolutionary trajectory with time in response to a series of driving variables acting at various spatial and temporal scales (e.g., Brierley et al., 2008; Dufour and Piégay, 2009).

Rivers continuously adjust their morphology through time in response to changes in boundary conditions, such as variations in fluxes of water and sediment. Each river may have specific characteristics determined by its historical evolution, including human factors and particular sequence of events, so interpretation of local temporal adjustments in morphology is essential for assessing current conditions and possible future adjustments and scenarios.

Awareness that current river morphology is simply a point along a variable evolutionary trajectory implies that in most cases a ‘recovery’ to a historical or ‘pristine’ state cannot take place because of completely changed boundary conditions (Dufour and Piégay, 2009), and that identification of a morphological ‘reference state’ defined in terms of processes should be considered in setting restoration goals. The dynamic nature of rivers also implies that a well-defined channel geometry is rarely achievable as a morphological target condition for restoration. Instead the ‘reference condition’ concept should be replaced by a targeted, objective-based strategy that accounts for less human influence driving natural processes and the ecosystem services associated with them (Dufour and Piégay, 2009). In this sense, restoration targets should be consistent with the current and future natural morphological potential and should be supported by an historical analysis of the evolutionary trajectory and by assessing disruptions to the primary driving processes (Kondolf et al., 2001; Beechie et al., 2010).

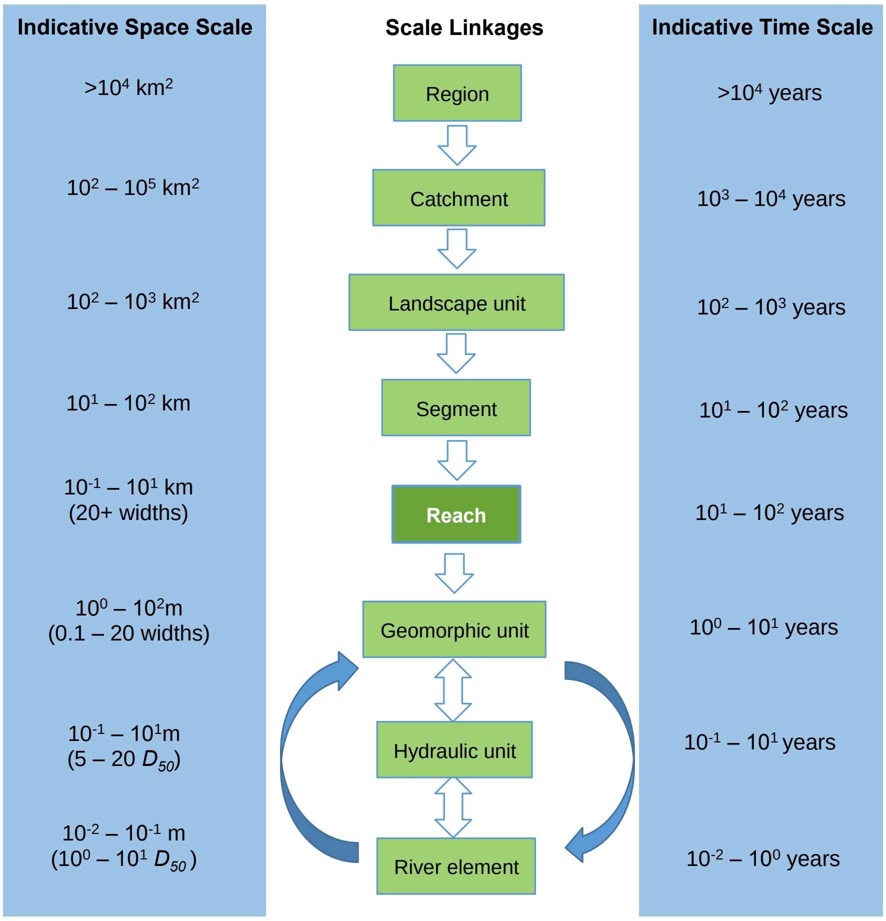


Figure 2.1 Hierarchy of spatial scales for the European Framework for Hydromorphology, including indicative spatial dimensions and timescales over which these units are likely to persist (from Gurnell et al., 2014).

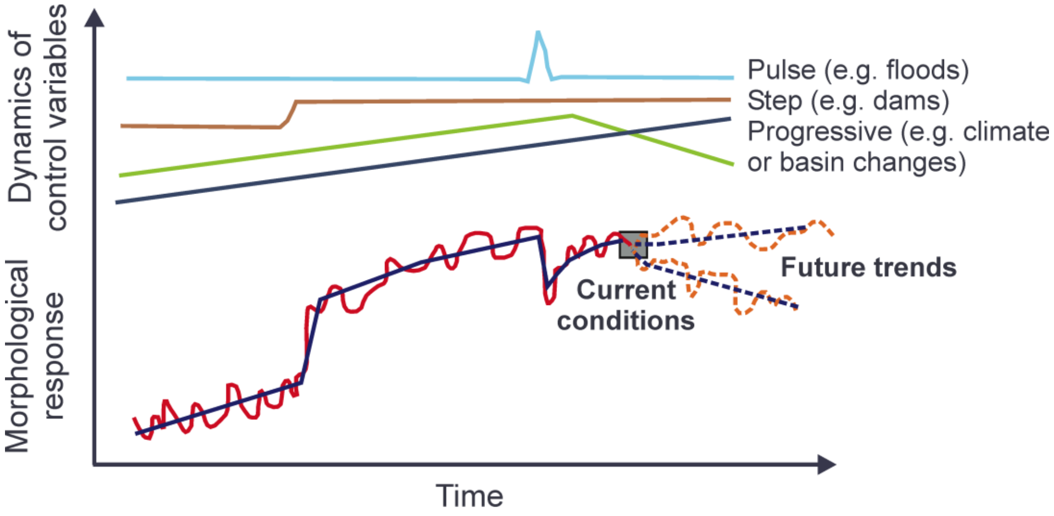


Figure 2.2 The concept of an evolutionary trajectory (modified from Dufour & Piégay, 2009).

2.2 The Overall Framework

The overall spatio-temporal framework for assessment, analysis, and monitoring of hydromorphological conditions presented in this document directly stems from the multi-scale methodological procedure developed in REFORM deliverable D2.1 (Gurnell et al., 2014). Four main stages are identified (Figure 2.3): (1) delineation and characterization of the river system; (2) assessment of past temporal changes and current river conditions; (3) future trends; (4) identification of management actions.

(1) Catchment-wide delineation and spatial characterization of the fluvial system. This phase delineates, characterises and analyses the catchment and river system in their current conditions.

(2) Assessment of temporal changes and current conditions. This phase involves reconstructing the history and evolutionary trajectories of morphological changes that have resulted in present river conditions.

(3) Assessment of scenario-based future trends. This phase identifies possible future scenarios of hydromorphological modification.

(4) The final phase identifies possible hydromorphological restoration or management actions, and strongly interacts with the identification of restoration potential and strategies developed in the REFORM WP5.

Each stage contains a series of procedural steps that are followed to conduct an assessment of river conditions and lastly to support the selection of appropriate management actions in a meaningful, coherent, and consistent manner.

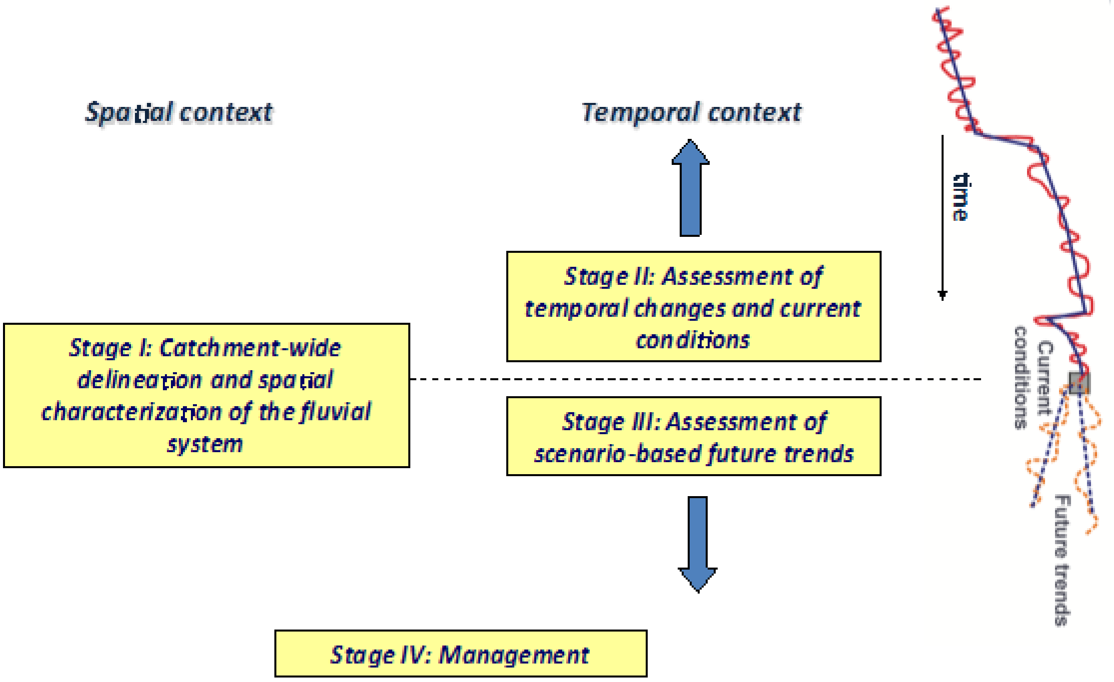


Figure 2.3 Structure of the overall hydromorphological framework. On the right side, the graph emphasises that the present state of the river system represents a spot within a long trajectory of evolution that needs to be known to understand current conditions and possible future trends.

Box 2.1: Definition of terms used in the framework

Delineation (or *segmentation*): delimitation of the boundaries of the spatial units of a catchment and its river system.

Characterization: description of the spatial units of a catchment and its river system to support understanding of system functioning.

Assessment: evaluation of the conditions and functioning of the spatial units of a catchment and its river system.

Monitoring: periodic measurement (or evaluation) of parameters or indicators to assess the changes that are occurring.

Modelling: simplifying abstraction or idealization of reality that results in quantitative or qualitative understanding of how the system could change in the future.

Prediction: qualitative or quantitative description of how forms or processes could evolve in the future.

Evaluation: systematic and structured determination, interpretation or judgement.

Key features and applications of the REFORM hydromorphological framework

- The framework provides a **flexible set of procedures** that can be used to conduct a catchment-based survey and assessment. The approach is **open-ended** to the extent that member states can incorporate their own data sets and methods.
- The framework is organised in a **sequence of stages**, each one containing a series of **procedural steps** that support the assessment of river conditions in a meaningful, coherent, and consistent manner.
- It is not necessary to carry out all of the steps. The steps that need to be included depend on the **degree of detail** that is needed and the **specific problems** to be addressed. The components of the framework can be adjusted and **additional indicators or tools** can be incorporated to expand the details of any assessments to suit local circumstances.
- Application of a catchment-based, hierarchical framework allows representative reaches or sites to be selected for **monitoring river conditions**, and for appropriate upscaling or downscaling of information.
- The framework can be used to classify and **understand current conditions** and to assess the **potential for morphological changes**.
- The framework can also be used to support **prioritisation of actions** and selection of **sustainable management strategies**.

Ecological relevance

- *Physical processes and structures are relevant to the provision of habitats to support the entire life cycle of organisms including refuge, feeding, spawning habitats, etc. Thus, a process-based, multi-scale understanding of hydromorphology is essential for identifying degraded segments and reaches of rivers and for developing sustainable restoration approaches consistent with hydromorphological functioning from catchment to reach scales.*

Links

- The REFORM Deliverable D2.1 (Gurnell et al., 2014)
- A summary of the D2.1 methodology is reported in Gurnell et al. (2015a)
- Existing geomorphological frameworks with a similar structure are the *River Styles Framework* by Brierley and Fryirs (2005), and the *IDRAIM* methodology by Rinaldi et al. (2015) which is also available in Italian

3. Stage I: Catchment–wide delineation and spatial characterization of the fluvial system

Stage I undertakes a catchment-wide delineation, characterization and analysis of catchment and river system in their current condition in two steps: (1) delineation of spatial units; (2) characterization of spatial units.

Delineation subdivides the catchment and river network into a hierarchy of spatial units, where the reach is the key spatial scale useful for the assessment of hydromorphological conditions.

Once the spatial units have been delineated, their properties are quantified during the characterization phase, and then appropriate characteristics are used to define indicators of processes, forms and human interventions.

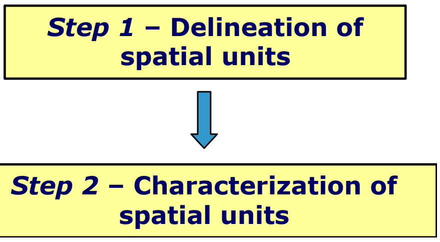


Figure 3.1 Steps of the Stage I.

For the theoretical background and a wider description of the multi-scale, hierarchical framework, refer to REFORM Deliverable D2.1 (Gurnell et al., 2014). This chapter summarizes the methodology.

3.1 Step 1: Delineation of spatial units

Delineation subdivides the catchment and river network into a hierarchy of spatial units, where the reach is the key spatial scale for the assessment of hydromorphological conditions.

The hierarchy of spatial units within which relevant properties, forms and processes can be investigated is illustrated in Figure 2.1. A summary of definitions and delineation criteria for each spatial unit is provided in this section.

Basic Questions of Stage I - Step 1

- What are the *landscape units* within the catchment and what are the factors (geology, elevation, relief, vegetation coverage) that can be used to differentiate them?
- Do *segments* derived from the boundaries of landscape units need to be further divided based on additional factors (e.g., major changes in valley gradient, valley lateral confinement, catchment area)?
- What morphological *river types* are found in the investigated river network, and do these suggest that segments need to be subdivided into *reaches*?
- Are there *additional factors* (e.g. reach-scale changes in confinement setting, bed slope, sediment calibre, discharge and sediment supply associated with tributary confluences or artificial discontinuities) that should also be considered for *reach delineation*?

The multi-scale procedure is designed to be suitable for management application by environmental or water agencies. The approach is deliberately open-ended to allow for optimum use of locally available data sets, particularly information already gathered to meet WFD requirements. Therefore, the delineation is largely based on existing information (e.g., topographical, geological, land use data) and remote sensing data analyzed within a GIS. The requirement for the collection of new data is kept to a minimum. The spatial extent and detail of the delineation varies depending on management objectives and the size of the catchment:

- For smaller catchments or where there are multiple objectives, the entire catchment is subdivided into a complete set of spatial units from catchment to reach scale.
- In large catchments, delineation of the complete set of units may not be feasible. Under such circumstances, a complete set of landscape units and segments is delineated, but reaches are only delineated for specific portions of the catchment or for specific river segments that require detailed investigation.
- Where the interest is on one or more specific reaches, a minimum delineation should focus on the spatial units (landscape units and segments) containing the investigated reach(es), at least in the first instance.

Delineation is achieved through a flexible and adaptive procedure rather than a rigid set of rules. Recent developments in automated spatial disaggregation and discretization of fluvial features (e.g., Alber and Piégay, 2011) could potentially be implemented for some steps of the procedure (an example application of automated delineation of river reaches is reported in Deliverable 2.1, Part 2, Annex A).

Definitions, delineation criteria, methods and data sources for each spatial scale are summarized below.

Region
Alternative equivalent terms **Ecoregion, Biogeographical region**
Indicative space and time scale **$> 10^4$ km^2** **$> 10^4$ yrs**
Description **Relatively large area containing characteristic assemblages of natural communities and species that are the product of climate, relief, tectonic processes, etc.**
Delineation criteria **Differences in main climatic variables and distribution of 'natural' vegetation types.**
Methods and data sources **www.globalbioclimatics.org, using Biogeographic Region and Sub-Region.**

Catchment
Alternative equivalent terms **Drainage basin, Watershed**
Indicative space and time scale **$10^2 – 10^5$ km^2** **$10^3 – 10^4$ yrs**
Description **Area of land drained by a river and its tributaries.**
Delineation criteria **Topographic divide (watershed).**
Methods and data sources **Digital Elevation Models (e.g. SRTM, ASTER GDEM) using GIS algorithms to delimit the topographic divide.**

Landscape unit

Alternative equivalent terms
Physiographic unit, Process domain

Indicative space and time scale
10^2 – 10^3 km^2
10^2 – 10^3 yrs

Description
Portion of a catchment with similar landscape morphological characteristics (topography/landform assemblage).

Delineation criteria
Topographic form (elevation, relief – dissection, often reflecting rock type(s) and showing characteristic land cover assemblages).

Methods and data sources
GIS overlay of some of the following in the stated order of priority: (1) Digital Elevation Model (e.g. SRTM, ASTER GDEM); **(2) Geological maps (One Geology Europe); (3) CORINE Land Cover; (4) Supporting information from: Google Earth / Orthophotos.**

Segment

Alternative equivalent terms
Sector

Indicative space and time scale
10^1 – 10^2 km
10^1 – 10^2 yrs

Description
Section of river subject to similar valley-scale influences and energy conditions

Delineation criteria
Change of landscape unit (e.g. abrupt change in geology); major changes of valley gradient; major tributary confluences (significantly increasing upstream catchment area and river discharge); valley confinement (confined, partly-confined, unconfined); in mountainous areas, very large lateral sediment inputs.

Methods and data sources
DEMs; Google Earth images; Orthophotos. 1) Major segments are identified by applying GIS tools to a DEM with river network overlay, to define downstream breaks in valley gradient (and width) and in upstream contributing area; (2) Major segments may be further subdivided according to distinct changes in valley confinement.

Reach

Indicative space and time scale
10^{-1} – 10^1 km
(20+ widths)
10^1 – 10^2 yrs

Description
Section of river along which boundary conditions are sufficiently uniform that the river maintains a near consistent internal set of process-form interactions (a river segment can contain one to several reaches).

Delineation criteria
Channel morphology (particularly planform: see Basic River Typology, Table 3.1, Figure 3.2) (minor changes in bed slope, sediment calibre, may be relevant); floodplain features; artificial discontinuities that affect longitudinal continuity (e.g. dams, major weirs / check dams that disrupt water and sediment transfer).

Methods and data sources

Segments are subdivided into reaches by visual interpretation of consistent river and floodplain (bio) geomorphic pattern using: Google Earth; Orthophotos; Multi-spectral remotely-sensed data; Lidar data; (Field reconnaissance can provide useful confirmation / additional data).

Geomorphic unit

Alternative equivalent terms
Morphological unit, Meshohabitat, Sub-reach or Site

Indicative space and time scale
$10^0 – 10^2$ m
(0.1 – 20 widths)
$10^0 – 10^1$ yrs

Description
Area containing a landform created by erosion and/or deposition inside (instream geomorphic unit) or outside (floodplain geomorphic unit) the river channel. Geomorphic units can be located within the channel (bed and mid-channel features), along the channel edges (marginal and bank features) or on the floodplain, and include secondary aquatic habitats within the floodplain.

Delineation criteria
Major geomorphic units of the channel or floodplain distinguished by distinct form, sediment structure / calibre, water depth/velocity structure and sometimes large wood or plant stands (e.g. aquatic / riparian, age class)

Methods and data sources
Requires field survey but preliminary analysis can use: Google Earth; Orthophotos; Multi-spectral remotely-sensed data; Lidar data

Hydraulic unit

Alternative equivalent terms
Microhabitat

Indicative space and time scale
$10^{-1} – 10^1$ m
(5 – 20 D_{50})
$10^{-1} – 10^1$ yrs

Description
Spatially distinct patches of relatively homogeneous surface flow and substrate character (a single geomorphic unit can include from one to several hydraulic units)

Delineation criteria
Patches with a consistent flow depth / velocity / bed shear stress for any given flow stage and characterized by narrow range in sediment calibre

Methods and data sources
Field survey; Hydraulic modelling

River element

Alternative equivalent terms
Microhabitat

Indicative space and time scale
$10^{-2} – 10^{-1}$ m
(10^0 – 10^1 D_{50})
$10^{-2} – 10^0$ yrs

Description
Elements of river environments including individuals and patches of sediment, plants, wood, etc.

Delineation criteria
Significant isolated elements creating specific habitat or ecological environments

Methods and data sources
Field survey

3.1.1 Basic River Typology (BRT)

The first level of reach morphological classification consists of a simple procedure based on river channel planform character (number of threads and planform pattern) framed in the context of valley setting (confinement).

The BRT classifies reaches using readily-available information, mainly remotely-sensed imagery. The typology defines seven river types (plus a type 0 for highly altered reaches) (Table 3.1, Figure 3.2). Different channel morphological types are associated with two broad categories of valley confinement (i) confined reaches, and (ii) unconfined and partly-confined reaches.

Table 3.1 Basic River Typology based on Confinement and Planform.

Type	Valley Confinement	Threads	Planform	*Si*	*Bi*	*Ai*
0	Heavily artificial	Any	Any	Any	Any	Any
1	Confined	Single	Straight-Sinuous	n/a	approx. 1	approx. 1
2	Partly confined / Unconfined	Single	Straight	< 1.05	approx. 1	approx. 1
3	Partly confined / Unconfined	Single	Sinuous	1.05 < *Si* < 1.5	approx. 1	approx. 1
4	Partly confined / Unconfined	Single	Meandering	>1.5	approx. 1	approx. 1
5	Confined / Partly Confined / Unconfined	Transitional	Wandering		1 < *Bi* < 1.5	*Ai* < 1.5
6	Confined / Partly Confined / Unconfined	Multi-thread	Braided		*Bi* > 1.5	*Ai* < 1.5
7	Confined / Partly Confined / Unconfined	Multi-thread	Anabranching		*Bi* < 1.5 or *Bi* > 1.5	*Ai* > 1.5

In the case of confined reaches, streams are divided into three categories (Table 3.1) based on the number of threads, i.e. single-thread; transitional (wandering); multi-thread. For single-thread, confined reaches (type 1), sinuosity is not meaningful as it is determined by the valley rather than the channel planform. Therefore, these channels are not further subdivided at this stage, because it is not possible to make accurate distinctions based on other characteristics, particularly the bed configuration, from remotely sensed sources. Transitional and multi-thread confined reaches are identified using the same criteria as for unconfined and partly-confined transitional and multi-thread channels (see below). These confined channel types are usually sufficiently large to be discriminated by remote sensing. However, it may only be possible to confirm some small transitional or multi-thread streams following field survey, in which case they are classified as type 1 reaches during the delineation phase.

In the case of unconfined and partly confined reaches, six broad types (2. Single-thread: Straight; 3. Single-thread: Sinuous; 4. Single-thread: Meandering; 5. Transitional: Wandering; 6. Multi-thread: Braided; 7. Multi-thread: Anabranching) are distinguished (Table 3.1). The classification is based on a planform assessment (from aerial imagery) of three indices: sinuosity, braiding, and anabranching indices.

The sinuosity index (*Si*) is 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) (Brice, 1964; Malavoi and Bravard, 2010; Alber and Piégay, 2011).

The braiding index (*Bi*) is the number of active channels separated by bars at baseflow. The recommended method for estimating *Bi* is the average count of wetted channels in each of at least 10 cross sections spaced no more than one braid plain width apart (Egozi and Ashmore, 2008).

The anabranching index (*Ai*) is the number of active channels separated by vegetated islands at baseflow. Similarly to the braiding index, the recommended method for estimating *Ai* is the average count of wetted channels separated by vegetated islands in each of at least 10 cross sections spaced no more than the maximum width enclosing the outer wetted channels apart.

Lastly, it is important to identify reaches of sufficient length (of the order of at least 10 times the channel width) with highly modified characteristics (e.g. urban and other highly channelised / reinforced reaches) as a separate category (type 0), since their lateral stability and geomorphic units cannot reflect any 'natural' boundary conditions. In this case, the previous indices are not used as criteria to discriminate within this category.

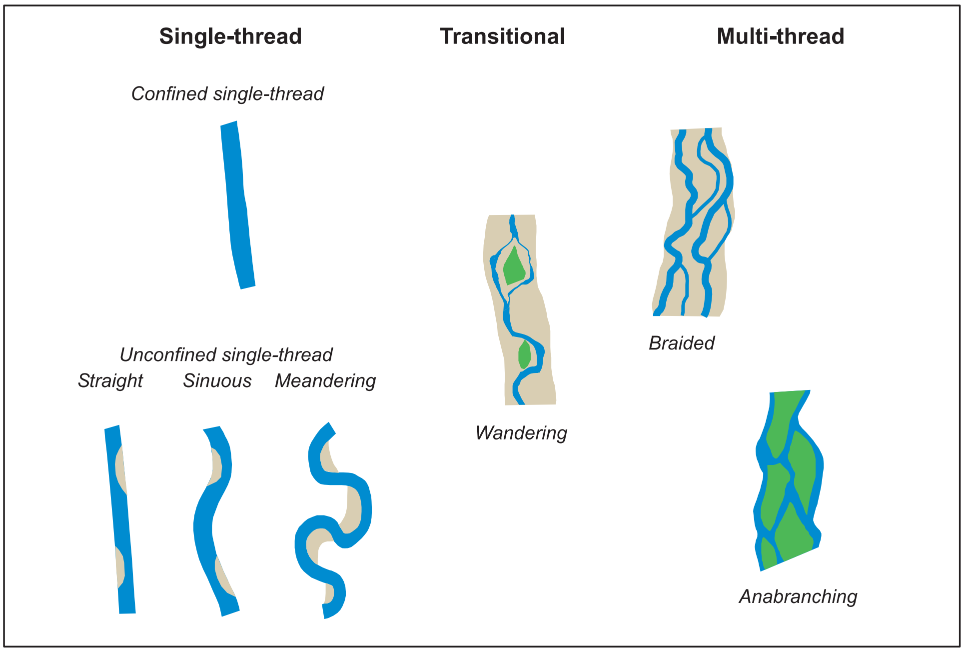


Figure 3.2 The seven main morphological types identified from remote sensing and used as one of the criteria for delineation of river reaches.

Main Outputs of Stage I - Step 1

- Synthesis of data sources used to define landscape units and segments, such as a catchment-based geological sketch, DEM, and longitudinal profile of valley gradient with contributing area plots.
- GIS map with landscape units, segments, and reaches.
- Summary Tables with a list of spatial units (landscape units, segments, and reaches), and information on delineation criteria used to define their boundaries.

3.2 Step 2: Characterization of spatial units

Having defined the boundaries of the spatial units (delineation), they are characterised or described to support understanding of their conditions and functioning and to provide information necessary for their assessment. A detailed description of data sources and characteristics that can be extracted at different spatial scales is reported in REFORM deliverable 2.1 (Gurnell et al., 2014), while a brief summary follows in this chapter.

Basic Questions of Stage I - Step 2

- What are the characteristics of the *catchment* (geology, topography, hydrology, vegetation cover, land use) and of the *landscape units* identified during the previous step?
- Where are the main *sediment sources* located within the catchment's landscape units and segments?
- What are the main *processes of sediment delivery* and wood recruitment (landslides, soil erosion, bank erosion, etc.) and their potential contribution to sediment production?
- What are the *characteristics of the river* and its corridor (lateral confinement, river morphology, channel dimension, river energy, bed and bank sediments, flow regime, floodplain, groundwater – surface water interactions, riparian and aquatic vegetation)?
- What are the assemblages of channel and floodplain *geomorphic units* characterising each river type?
- What are the physical *pressures* and human *impacts* on river processes and morphology? Are there barriers or artificial elements interrupting or altering longitudinal and/or lateral continuity?
- What are the catchment and landscape unit *controls* on river characteristics? For example, what is the downstream pattern of channel morphology and floodplain features and what are the main controls on such pattern? Why do changes occur at reach boundaries?

In the following sections, a series of indicators are listed for each of the spatial scales (section 3.2.1), and then four classifications that act as indicators are described in greater detail: an extended river typology (section 3.2.2) and floodplain typology (section 3.2.3) are applicable at the reach scale, whereas a flow regime typology (section 3.2.4) and a description of types of groundwater-surface water interaction (section 3.2.5) are more relevant to the segment scale.

3.2.1 Indicators

A series of properties can be used to characterise units at each spatial scale in the hierarchy. These are summarised as follows.

At the regional scale, macro-features of biogeography and hydroclimate provide broad boundary conditions for the characteristics of the study catchment at all spatial scales. Two properties are considered: (1) Main river basin or district; (2) Biogeographic Region or Ecoregion.

At the catchment scale, the aim is to give an overview of the topographic, geological and land cover controls on hydrological responsiveness and sediment delivery to the river network. Three properties are suggested: (1) Size, Morphology, Hydrological Balance; (2) Geology/Soils; (3) Land cover.

Landscape units are characterised in a similar way to the entire catchment but to a greater level of detail, including the following properties: (1) Water production; (2) Sediment production; (3) Physical pressures on sediment regime.

River segments are characterised according to: (1) Flow regime; (2) Valley characteristics; (3) Sediment; (4) Riparian corridor features; (5) Physical pressures.

River reaches are the key spatial units for the assessment of river conditions. They can be characterized by a combination of properties, including: (1) Channel dimensions (width, planform, gradient); (2) River energy; (3) Bed and bank sediment; (4) Riparian and aquatic vegetation; (5) Wood production; (6) Physical pressures.

Geomorphic units represent an important component of the characterization of the channel and the river corridor. At a first stage, characteristic geomorphic units can be extracted from aerial imagery and existing habitat / morphological surveys. Then, a purpose-specific field survey is needed to provide a comprehensive record of the geomorphic units existing within the active channel and alluvial plain. During this survey, additional information concerning hydraulic units and river elements within the geomorphic units can be collected.

Table 3.2 Summary of main hydromorphological indicators representative of processes at spatial scales from catchment to river segment.

Key Processes	Indicators (indicative units)
Catchment scale	
Water production	Catchment area (km^2)
	Average annual precipitation (mm)
	Average annual runoff / water yield (mm)
	Average runoff coefficient (dimensionless)
	Geology (% WFD classes)
	Land Cover (% CORINE level I classes)
Landscape unit scale	
Runoff production / retention	Exposed aquifers, permanent snow-ice cover (%)
	Soil permeability (% permeability classes)
	Large surface water bodies (% cover)
	Delayed, intermediate, rapid runoff production areas (% cover based on CORINE level 2, 3 land cover classes)
Sediment production	Soil erosion (t/ha/year)
	Coarse sediment source areas (unstable slopes, gullies, etc., ha, % area)
River segment scale	
Valley features	Valley confinement (categorical)
	Valley gradient (m/m, %)
	River confinement (valley width/river width, dimensionless)
River flow regime	Flow regime type (categorical)
	Average annual flow (m^3/s)
	Base flow index (categorical)
	Annual floods of different return periods (Qp_2, Qp_{10}, Qp_{median}, m^3/s)
	Timing of maximum and minimum flows (Julian day)
Sediment delivery and transport regime	Eroded soil delivery (t/year/km^2)
	Annual suspended load (t/year, t/km^2/year)
	Annual bed load (t/year, t/km^2/year)
	Sediment budget (categorical (gain, loss, balanced); t/year, t/km^2/year)
Disruption of longitudinal continuity of water, sediment and wood	Number of major (categorised as high and medium) blocking and spanning structures (e.g. dams, drop structures, weirs, bridges)
Riparian corridor size, functions, succession, wood delivery potential	Size of riparian corridor (average width, m)
	Longitudinal continuity / fragmentation of riparian vegetation along river edge (% of river length)
	River channel edges bordered by mature trees (i.e. potential sources of large wood, %)
	Dominant riparian plant associations

The information assembled during the characterization phase is based on a list of *indicators* that support the assessment of current and past functioning of the catchment and its spatial units (Stage II). Table 3.2 and 3.3 list the main indicators that reflect key hydromorphological processes from the catchment to the reach scale and that may act as characterization and classification criteria.

Table 3.3 Summary of main hydromorphological indicators representative of processes at reach scale (note: geomorphic units are used as reach-scale indicators).

Key Processes	Indicators (indicative units)
River reach scale	
Stream power	Specific stream power at contemporary bankfull width (Qp_2, Qp_{10}, Qp_{median}, W/m^2)
Flooding extent	% floodplain accessible by flood water
Channel type and dimensions	Average bankfull channel width (m), depth (m), width/depth, slope (m/m)
	Bed and bank sediment size (dominant size class, D50, cm)
	Channel type (categorical)
	Floodplain type (categorical)
	Presence of geomorphic units typical of channel and floodplain type (categorical scale)
Contemporary evidence of channel adjustments	Eroding banks (% active channel length)
	Laterally aggrading banks (% active channel length)
	Bed covered by bars, benches, islands (% area)
	Channel widening, narrowing, bed aggradation, bed incision (in each case indicated by the extent of indicative geomorphic units and assemblages, Yes if a sufficient % channel length is affected)
	Bed sediment structure (armouring, clogging) indicative of incision or aggradation (% channel bed area, categorical abundance scale)
	Riparian, emergent aquatic vegetation encroachment (% channel area)
Constraints on channel adjustments and water, sediment, wood continuity	Average width of erodible corridor (m)
	Longitudinal continuity (poor, intermediate or good categories, depends on number and type (high, medium, low) of channel blocking / spanning structures, e.g. dams, drop structures, weirs, bridges)
	(poor, intermediate or good categories, depends on proportion of channel banks erodible (unreinforced) (%) and proportion of river bed erodible (%))
Vegetation dynamics (riparian, aquatic vegetation and wood)	Proportion of riparian corridor with riparian vegetation (%)
	Dominant riparian tree species
	Riparian vegetation age structure (mature, balanced, immature categories, reflecting proportions under mature trees, shrubs, shorter vegetation, bare)
	Lateral gradient in riparian vegetation (strong, subdued, absent categories)
	Patchiness of riparian vegetation (strong, some, none categories)
	Presence of large wood and fallen trees in channel and riparian corridor (absent, occasional, present, abundant categories)
	Wood budget (good, moderate, degraded, severely degraded categories, depends on presence of fallen trees and wood in channel and riparian corridor)
	Abundance of riparian tree and large wood associated geomorphic units (absent, occasional, frequent, abundant, abundant and diverse categories)
	Aquatic plant extent (% river bed)
	Aquatic plant patchiness
	Number of aquatic plant morphotypes or species
	Abundance of aquatic plant associated geomorphic units (absent, occasional, frequent, abundant, abundant and diverse categories)

3.2.2 Extended River Typology (ERT)

Based on the additional knowledge developed during the characterization phase, an extended classification of channel morphology (ERT) is applied during this step.
Twenty-two extended morphological types are identified (Table 3.4, Figures 3.3 and 3.4) and described according to their confinement (confined, partly confined, unconfined), dominant bed material calibre (bedrock, boulder, cobble, gravel, sand, silt), and planform (straight-sinuous, meandering, pseudo-meandering, wandering, braided, island-braided, anabranching).

Table 3.4 Main characteristics of the 22 morphological types of the Extended River Typology. ERT: Extended River Type; BRT: corresponding Basic River Type; C: Confined; PC: Partly confined; U: Unconfined.

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

Characterization of **bed sediment size** is needed for application of the extended morphological classification, and characterisation of **geomorphic units** supports the assessment of the functioning of each type. The **Geomorphic Units survey and classification System (GUS)** can be used in this context (see D6.2 Part 4). The spatial pattern of the morphological types and associated assemblage of geomorphic units is fundamental for interpreting fluvial processes and controls of the river at catchment scale.

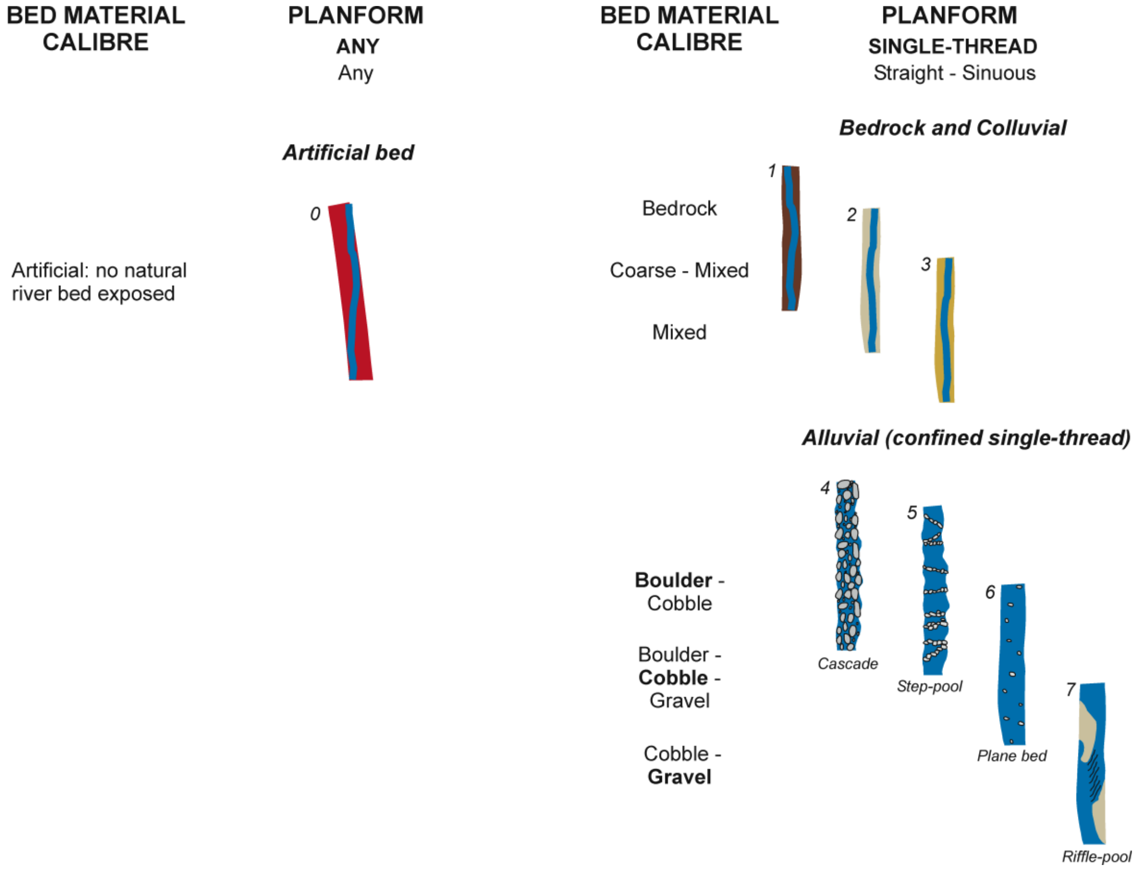


Figure 3.3 River types from 0 to 6 of the Extended River Typology.

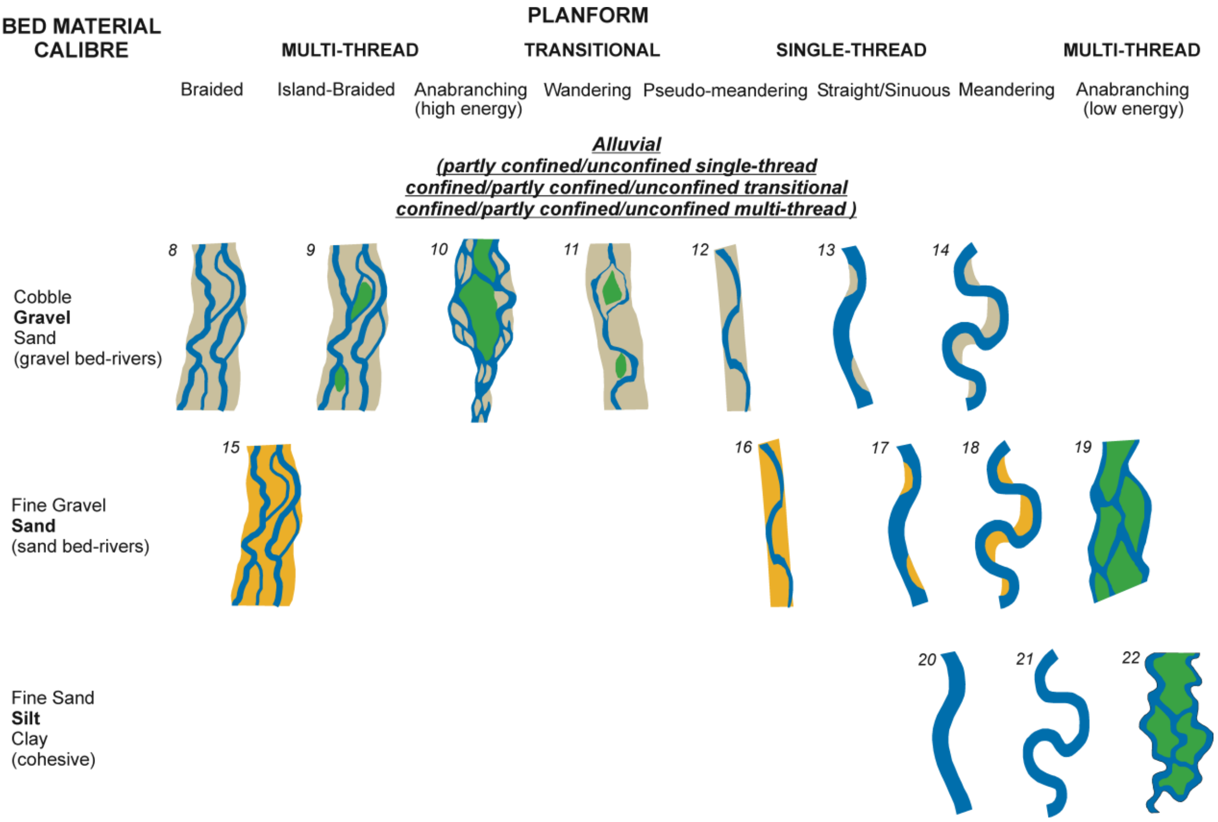


Figure 3.4 River types from 7 to 22 of the Extended River Typology.

The twenty-two extended types are not an exhaustive list of possible combinations of planform, morphological units, valley setting and sediment size, but rather an indicative, general framework for identifying catchment- or region-specific ranges of morphologies. This is because river characteristics cannot be neatly divided into classes; they vary continuously and thus transitional types are likely to be encountered quite frequently (Kondolf et al., 2003).

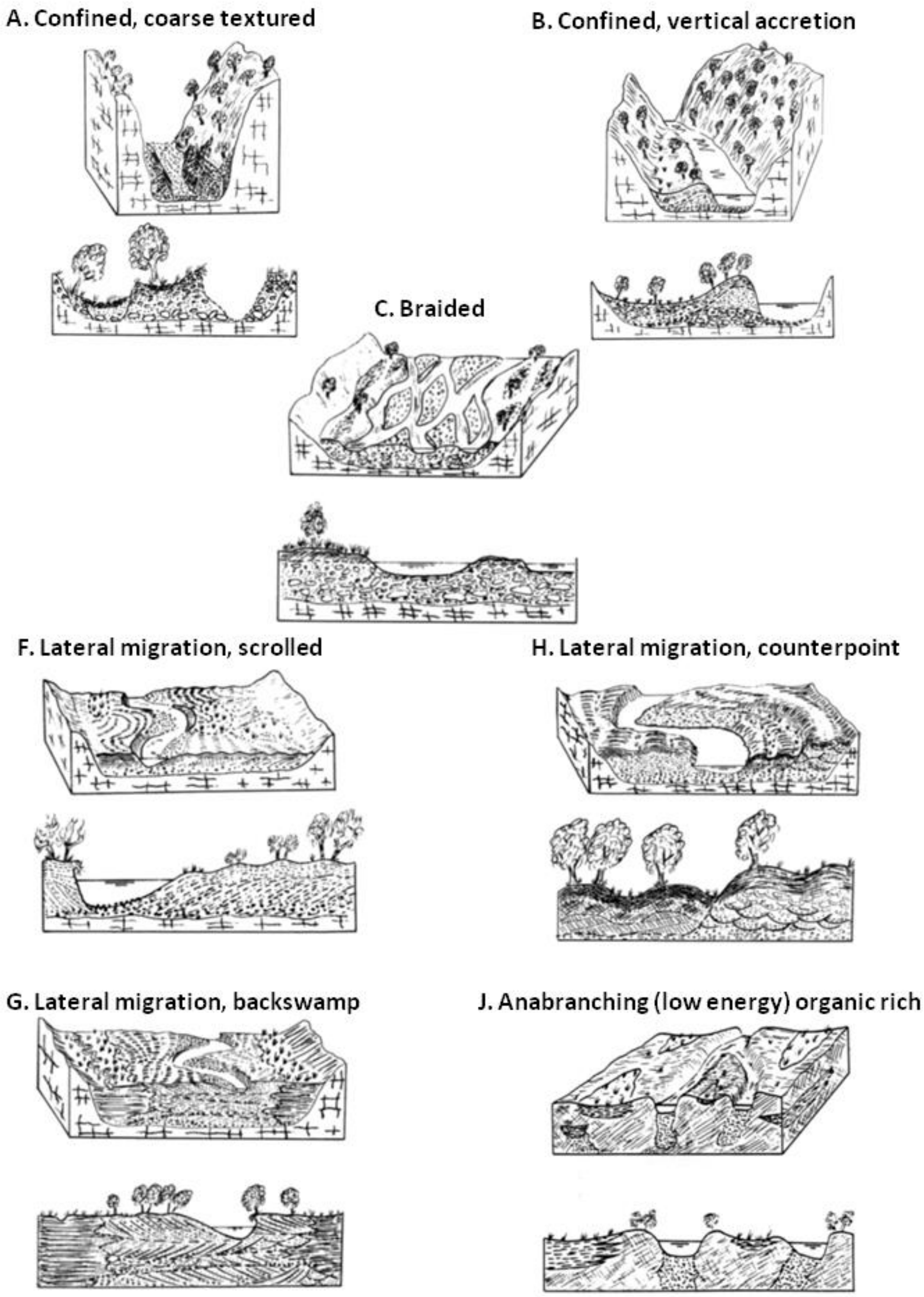
3.2.3 Floodplain Typology

The extended classification of river types is designed to provide a simple means for managers to allocate a river reach to a type. In many cases the observed planform may be an artefact of human modifications to the reach or to larger spatial units that influence the reach. However, the presence of geomorphic units, bed sediment calibre and apparent channel stability that are appropriate to the river type provide evidence concerning whether or not a particular reach is functioning in accordance with its type. Since alluvial rivers provide the sediments to build their floodplains, the characteristics of the floodplain provide further evidence that the river is functioning in an appropriate way for its type.

Nanson and Croke's (1992) floodplain classification, which is based on river energy (bankfull unit stream power) and floodplain sediments (non-cohesive or cohesive) has been adapted to recognise broad categories of floodplain and link them to the extended river types that may have constructed them. Table 3.5 summarises 10 broad types of floodplain that are likely to be encountered widely across Europe, and a further three types (described by Nanson and Croke for semi-arid environments), which may have some relevance to the driest parts of Europe. Seven of the ten floodplain types listed in Table 3.5 that are likely to be widely encountered across Europe are represented in Figure 3.5.

Table 3.5 – Classification of Floodplain Typology (FT).

ERT	Floodplain Class	Floodplain Type (FT)	Unit stream power ($W\ m^{-2}$)
(1), 2, 4, 5	High energy, non-cohesive floodplains	A. Confined, coarse textured	> 1000
3, 6, 7		B. Confined, vertical accretion	300 – 1000
8, 9, 15	Medium energy, non-cohesive floodplains	C. Braided	50 – 300
10, 11		D. Wandering, gravel-bed	30 – 200
12, 13		E. (Sinuous / meandering) lateral migration, non-scrolled	10 – 60
13, 14		F. (Sinuous / meandering) lateral migration, scrolled	10 – 60
16, 17, 18		G. (Sinuous / meandering) lateral migration, backswamp	10 – 60
17, 18		H. (Partly-confined, sinuous / meandering) lateral migration, counterpoint	10 – 60
20, 21	Low energy, cohesive floodplains	I. Laterally stable	< 10
19, 22		J. Anabranching (low energy), organic rich	< 10
Floodplain types defined by Nanson and Croke (1992) that are unlikely to be encountered in Europe			
20 (semi-arid)	High energy, non-cohesive floodplains	K. Unconfined, vertical accretion, sandy	300 – 600
16 (semi-arid)		L. Cut and fill	~ 300
19, 22 (semi-arid)	Low energy, cohesive floodplains	M. Anabranching (low energy), inorganic	< 10



A. Confined, coarse textured

B. Confined, vertical accretion

C. Braided

F. Lateral migration, scrolled

H. Lateral migration, counterpoint

G. Lateral migration, backswamp

J. Anabranching (low energy) organic rich

Figure 3.5 Seven of the ten floodplain types listed in Table 3.5 that are likely to be widely encountered across Europe (three types are excluded: type D – wandering is excluded because it is a mixture of other types; types E and I are excluded because these floodplains are relatively featureless) (Diagrams from Nanson and Croke, 1992).

3.2.4 Flow Regime Typology (FRT)

Starting from the classification scheme proposed by Poff & Ward (1989) and Poff (1996) for the streams in the United States, a classification in flow regime types (FRT) applicable to European rivers has been developed (Bussettini et al., 2014). The following characterization criteria are considered: (i) intermittency; (ii) river-aquifer interaction

(Boni et al., 1993); (iii) prevailing type of river flow source (Poff and Ward, 1989; Poff, 1996; Poff et al., 1997).

The classification is based on threshold values of the hydrological indicators summarised in Table 3.6. The threshold ‘ZERODAY’>0 separates ‘intermittent’ from ‘perennial’ regimes. Subdivision of ‘intermittent’ regimes adopts different values of the ‘ZERODAY’ indicator which have been previously identified and calibrated on the rivers of the Mediterranean areas of Europe by Oueslati et al. (2010). Subdivision of ‘perennial’ flow regimes use combinations of threshold values of several indicators (FLDPRED, FLDTIME, BFI, DAYCV, Figure 3.6 and Table 3.7).

Table 3.6 Hydrological indicators used for the classification of Flow Regime Types.

Acronym	Extended name	Definition
DAYCV	Daily discharge coefficient of variation (%)	Average (across all years) of the standard deviation of daily discharge divided by the annual mean discharge (× 100)
FLDFREQ	Flood frequency (1/yr)	Average number of floods per year with discharge higher than the mean annual maximum daily discharge (flood threshold)
FLDPRED	Seasonal flood predictability	Maximum proportion of all peaks over the discharge threshold (POT) that falls in one of the twelve “60-day seasonal windows” (Jan-Feb,..., Dec-Jan), divided by the total number of POTs.
FLDTIME	Timing of floods (day)	First day of the 60-day seasonal windows when FLDPRED is highest. The first 60-day period is January-February and the last one is December-January
BFI	Base Flow index (%)	Proportion between the “minimum of monthly discharge” and “mean monthly discharge’, multiplied by 100
ZERODAY	Extent of intermittency (number of days)	Average annual number of days having zero discharge

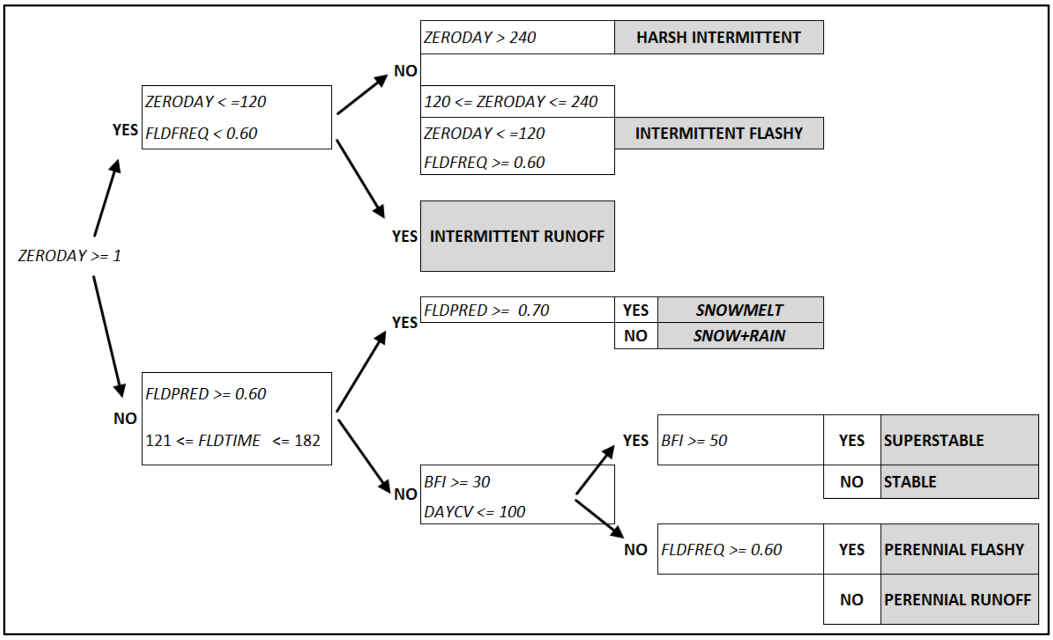


Figure 3.6 Conceptual model of Flow Regime Classification.

Data required for the application of this method consist of long-term series of daily data flow (average daily flow); at least 20-years of records are required for a robust analysis (Huh et al. 2005). The classification model assigns a hydrological type to each gauged stream whose discharge time series has been estimated. Within the hierarchical framework, the flow regime type (FRT) is estimated at the segment scale, given that typically, variability of flow regime occurs at a larger spatial scale than the reach. Therefore, reaches are classified in terms of FRT by the class assigned to the segment within which they are located.

Table 3.7 Classification of Flow Regime Type.

Class	Definition
I. Temporary streams	
1. Harsh Intermittent (HI)	Streams without flow for almost the whole year. Flow is activated during intense rainfall (e.g., streams of the Southern Europe and Mediterranean areas).
2. Intermittent Flashy (IF)	Streams with runoff in the river bed for less than 8 months/year; runoff is present occasionally, because of rainfall, snowmelt or seasonal fluctuations of the aquifer level.
3. Intermittent Runoff (IR)	Stream with runoff in the river bed for more than 8 months/year.
II. Perennial rivers fed predominantly by snowmelt	
4. Perennial Snowmelt (SN)	Streams prevailingly fed by snow and glacier melt.
5. Perennial Snow-rain (SR)	Streams fed by a mix of surface runoff and snow melt.
III. Perennial rivers fed predominantly by groundwater	
6. Perennial Super-stable (SS)	Rivers with very low variability of the flow regime; in the case of unregulated rivers (natural regime), these are predominantly groundwater fed (baseflow).
7. Perennial Stable (SG)	Rivers having a stable flow regime, due to the regulation effect of groundwater; in the case of unregulated rivers, flow is predominantly fed from groundwater (baseflow).
IV. Perennial rivers fed predominantly by surface runoff	
8. Perennial flashy (PF)	Rivers fed predominantly by surface runoff (quick flow), with high flashiness of floods. Flow regime is highly influenced by intense flood events and seasonal droughts.
9. Perennial runoff (PR)	Rivers fed predominantly by surface runoff (quick flow) and groundwater (baseflow). Flow regime is characterized by low seasonal variability.

3.2.5 Groundwater – Surface water Interactions (GSI)

A critical hydrological aspect of the 22 river types that strongly affects their flow regime as well as their ecology is the nature and extent of any groundwater-surface water interactions (GSI) that are likely to occur. One important aspect of river ecology that feeds back into river morphology, is the type, density and vigour of any riparian and aquatic vegetation that is present. This is heavily dependent upon water availability (access to soil moisture and near-surface groundwater) and river flow reliability and energy / disturbance (the river flow regime) (Gurnell, 2014). Therefore, GSI have been addressed as well as the flow regime in the baseline categorisation of river types. The river flow regime type is a first indicator of the importance of GSI, but the nature of any GSI has also been categorised, reflecting the geological and climatic setting of each river morphological type, including the nature and confinement of the floodplain or corridor. The interactions fall into four main groups, depending upon predominant valley confinement and the calibre of the substrate: (i) confined bedrock or colluvial channels, (ii) mainly confined alluvial channels on coarse substrates, (iii) confined, partly-confined or unconfined alluvial channels on intermediate (gravel-sand) substrates, or (iv) partly confined / unconfined alluvial channels on fine (silt/clay) substrates. A total of 10 possible GSI with climate-related subtypes have been identified within these four broad groups in relation to the different classes of the ERT, and are summarised in Table 3.8.

Table 3.8 Typical Groundwater – Surface water Interactions (GSI). In bold: dominant bed material type / calibre.

ERT	Bed material calibre	Typical GSI
A. Confined bedrock and colluvial channels		
1	**Bedrock**	No GSI or limited GSI with phreatic aquifer formed by the colluvial. Additionally, if permeable faults or fracture zones are present, local GSI in these zones. Local flow paths are likely to be dominated by direct exchange through river bedding and overland flow over bedrock river banks.
2	**Coarse mixed**	
3	**Mixed**	
B. Confined alluvial channels on coarse substrates		
4	**Boulder**	Local GSI with phreatic groundwater body via river bedding. In case the phreatic aquifer is connected to deeper groundwater bodies, GSI at (sub-) catchment scale with deep semi-confined aquifers occurs. Local flow paths are likely to be dominated by overland flow on the river banks and direct exchange through river bedding.
5	**Boulder**, Cobble,	
6	Boulder, **Cobble**, Gravel	
7	Cobble, **Gravel**	
C. Partly confined, unconfined (or confined multi-thread) alluvial channels on intermediate (gravel-sand) substrates		
8-11	**Gravel**, sand	Extensive GSI with phreatic groundwater body at reach scale in riparian zone (only unconfined reaches) and via river bedding. In case the phreatic aquifer is connected to deeper groundwater bodies, GSI at (sub-) catchment scale with deep semi-confined aquifers occurs. Local flow paths in the riparian zone are likely to be dominated by diffuse flow or direct exchange through river bedding.
12-13		
14	Fine gravel, **sand**	
15		
16-18		
19		
D. Partly confined, unconfined (or confined multi-thread) alluvial channels on fine (silt-clay) substrates		
20-21	Fine sand, **silt**, clay	Limited and/or localized GSI with phreatic groundwater body at reach scale in riparian zone (only unconfined reaches) and via river bedding. In case the phreatic aquifer is connected to deeper groundwater bodies, GSI at (sub-) catchment scale with deep semi-confined aquifers occurs. The fine sediment fraction of the substrates prevents large GSI fluxes, and may cause local GSI in zones with higher permeability. Otherwise, local flow paths in the riparian zone are likely to be dominated by overland flow or drainage.
22		

3.2.6 Physical pressures

An overview of the physical pressures acting at different spatial scales that need to be characterised at this stage is reported in Table 3.9.

Table 3.9 Summary of physical pressures that need to be assessed at different spatial scales.

Landscape unit scale
Types of pressures Major transverse structures, including hydropower plants, which cause major disturbances of the natural sediment regime, in terms of continuity of sediment and woody debris
Methods and data sources Map layers of interventions, aerial images, topographic maps
Segment scale
Types of pressures Structures affecting longitudinal continuity of hydromorphological processes, including water transfer or abstraction, flow regulation, major points of sediment interventions (dredging, gravel mining), blocking (dam / check dam / weir / pier-deflector) structures and spanning / crossing structures (bridges)
Methods and data sources Map layers of interventions, aerial images, topographic maps
Reach scale
Types of pressures (1) River bed: artificially reinforced bed; channel blocking structures (subset of the segment scale data); sediment, wood, aquatic vegetation removal from the active channel;

(2) Riverbanks: bank reinforcements
(3) Riparian corridor: artificial levées, infrastructures (buildings, roads, etc.), vegetation management activities (partial or total cutting of riparian vegetation, wood removal)

Methods and data sources
Map layers of interventions, aerial images, field reconnaissance

Main Outputs of Stage I - Step 2

- Summary Tables describing the characteristics of catchment and landscape units.
- Summary Table of hydrological characteristics and indicators for the existing gauging stations in the catchment used to define their Flow Regime Type.
- GIS maps, synthetic tables and/or graphs summarising sediment sources and delivery.
- Tables summarising the characteristics of the river and its corridor for each reach (lateral confinement, river morphology, channel dimension, river energy, bed and bank sediments, floodplain, groundwater – surface water interactions, riparian and aquatic vegetation).
- Summary Tables with typical assemblages of geomorphic units characterising each river type.
- Summary Table and GIS map synthesising the main physical pressures and impacts at catchment scale (e.g., dams, check dams, fixed reaches, etc.).
- Graphs visualising the spatial patterns of some morphological parameters (e.g., bed slope, channel width, floodplain width) and their control on channel morphology.

Box 3.1: Links between River Reaches and the WFD Water Bodies

What are the relations between hierarchical spatial units and *water bodies* defined in the context of the WFD?

The REFORM multi-scale, hierarchical framework has relevance to the CEN (2004) guidance on the assessment of hydromorphology and also the definition of WFD water bodies. However, it is important to understand that the REFORM framework aims to be process-based with an explicit focus on understanding hydromorphology in a dynamic way that takes account of changes through time and across spatial scales. This is a different aim from the CEN (2004) guidance, which provides a protocol for 'recording the physical features of rivers' rather than providing any process-based understanding. It is also different from the WFD water bodies, which are management units that should be homogeneous with respect to the pressures that affect them and should not contain elements of differing ecological status. Therefore, more than hydromorphological factors influence their identification.

In relation to WFD water bodies, application of the REFORM framework to delineate segments often generates boundaries that correspond to WFD water body boundaries. Furthermore, there is no reason why these segments should not be subdivided using additional boundaries that correspond to those of water bodies.

The European Standard 'Water Quality – Guidance Standard for assessing the Hydromorphological Features of Rivers' (CEN, 2004) places a 'survey unit' assessment into the context of the WFD river typology (types A and B). Each catchment is subdivided into subcatchments or subareas (called 'river types'), based mainly on area, altitude, and geology. The river network within these subareas is then subdivided into 'reaches' based on similarity of geology, valley form, slope, planform, discharge (specifically inputs from significant tributary / change in stream order), land use, and sediment transport (lake, reservoir, dam, major weirs). Finally reaches are subdivided into survey units.

The REFORM framework uses a more standard geomorphological terminology for the spatial units and, although there is some correspondence in delineation criteria, the procedures recommended for the REFORM framework include a more comprehensive and explicitly process-based set of criteria. Thus, the REFORM framework defines catchments and landscape units which are not dissimilar to the WFD river types. It also defines segments and reaches, where the segments have many similarities to the CEN (2004) reaches but exclude planform as a criterion. This is because planform and other river channel characteristics can vary widely over much shorter river lengths than a segment. These shorter river lengths of similar river channel characteristics are defined as reaches in the REFORM framework. Thus in the REFORM framework, segments describe river lengths subject to a set of broadly consistent external controls on river geomorphology (valley confinement and gradient, land cover, flow amount and regime, etc.) whereas reaches refer to river lengths with similar local geomorphological controls and river channel characteristics (planform, bed and bank material and structure, assemblage of geomorphic units, etc.).

Influence of Hydromorphology on Biota and Ecosystem Function

In this box, some of the main controls and influences of hydromorphological processes on biota and ecosystem function are recalled (details are reported in the REFORM Deliverable D2.2 and in the references below).

I. Vegetation

The main hydromorphological controls on riparian vegetation are:
(i) *Climate*, from the biogeographical region and catchment until the reach scale (micro-climate). It determines the presence of specific plant species and communities ('potential' vegetation).
(ii) *Moisture availability*, from catchment (hillslopes) to segment and reach scales (within the river bed and on river margins). It depends on the flow regime (influenced by the climate at upper scales), soil permeability (and related aquifers) and river type (single-thread versus multi-thread). It determines the presence of specific plant species and communities ('potential' vegetation) at specific location within the river corridor, as well as plant growth performance.
(iii) *Fluvial disturbances*, at segment and reach scales. They depend on flow and sediment regimes at catchment and landscape unit scales and are moderated by valley setting (width, gradient, topography) and river type (e.g. channel width and transversal gradient of topography; Figure 3.7) at segment and reach scales, respectively. The magnitude, duration and timing of disturbance (inundation), shear stresses or drag by flow, sediment erosion or burial, all determine: the 'potential' vegetation (plants show different tolerance to disturbance), plant recruitment, establishment, growth and survival.

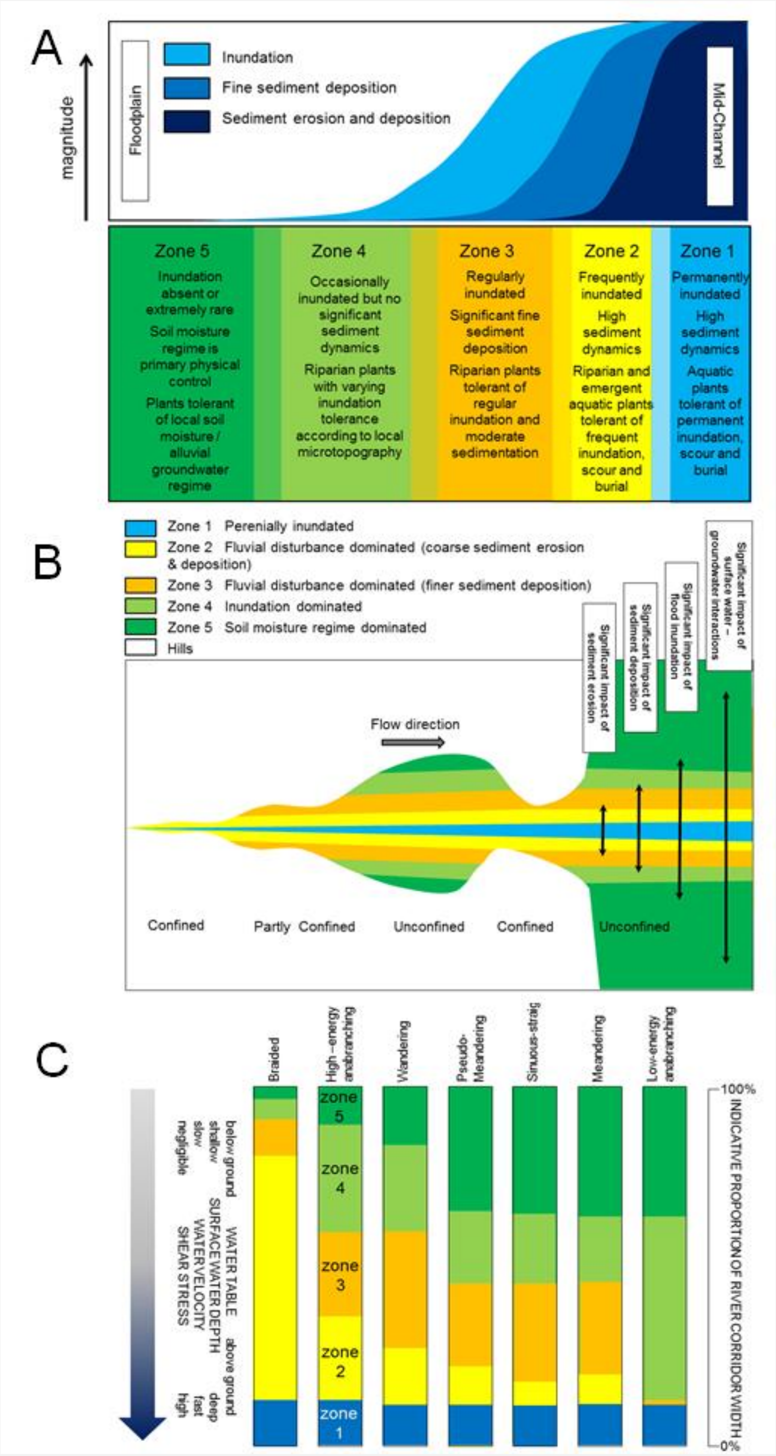


Figure 3.7 (A) Dominant hydrogeomorphological processes and their constraints on vegetation of five (temporally and spatially) dynamic zones of a river corridor. (B) Longitudinal and lateral variations in the dominant hydromorphological processes that influence vegetation composition, growth performance and turnover along a river located within a valley of varying confinement (C) Relative extent of the dominant hydromorphological process zones associated with rivers of different type. From Gurnell et al. (2015b).

II. Macroinvertebrates

The main hydromorphological controls on macroinvertebrates are (Table 3.10, Figure 3.8):

(i) *Climate*, at the region scale. Together with biogeography and evolutionary history of different taxa, it determines the long terms composition of macroinvertebrate community within catchments of a given region.

(ii) *Hydrologic, geologic, topographic and land cover conditions*, at the catchment scale. They determine the longitudinal gradient (continuum) of physical conditions along the river network. They influences the composition of the macroinvertebrate community at smaller spatial scales.

(iii) *Presence (or absence) and type of riparian corridor*, at the landscape unit and segment scales. It determines the input of coarse and dissolved organic matter (food source), and influence the type and structure of the macroinvertebrate community at segment and smaller spatial scales. It also supports the adult life stage of several species (e.g. dragonflies).

(iv) *Fluvial hydromorphological processes* (flow and sediment regime, in terms of erosion, deposition, transport), at the segment scale. They are influenced by the valley setting, the geology, the presence of tributaries and contribute to determine the habitat conditions for the macroinvertebrate community at smaller scales. The *longitudinal continuity* of processes, at the segment scale, is also included. Indeed high flow and flood events are responsible of the colonization by macroinvertebrates of new sites downstream. As well, the sedimentary continuity within the alluvial bed contributes to macroinvertebrate dispersal.

(v) *Habitat conditions and heterogeneity*, at the reach and smaller scales, are the most important hydromorphological controls on macroinvertebrate community. They are intended in terms of the presence and characteristics of different geomorphic and hydraulic units and river elements. Habitat conditions at the reach scale differ amongst river types and are imposed by hydromorphological controls at upper scales. The most important habitat conditions for macroinvertebrates are water depth, velocity and substrate grain size and their dynamics and variability across the channel, at the geomorphic and hydraulic unit scale as well as smaller scales (microhabitat). Other significant hydraulic variables at the microhabitat scale are Froude number, shear stress, Shield entrainment function. Sedimentary characteristics of the alluvium within the river bed (hyporheic interstitial environment) are also important, for e.g. as a refuge during disturbance events, for dispersal, for feeding. Habitat conditions and heterogeneity determine the macroinvertebrate community composition and structure at the reach and smaller scales, since macroinvertebrates display several adaptations to different habitat conditions (e.g. fast versus slow waters, coarse versus fine sediment). Macroinvertebrates may also adapt to different habitat conditions during a single species life cycle.

Table 3.10 Scale-dependent influences of water-related physical processes that determine the macroinvertebrate community according to their hydromorphological requirements (from Garcia De Jalon et al., 2015).

	Biogeographical context	HYMO Requirements				Trophic resources	Fluvial Disturbance
		Velocity	Substrate	Interstitial	Suspended solids		
Region	**Pool of potential native species**						
Catchment	Pool of potential native species				Hillslope erosion	Woody debris	Temperature L. gradients
Landscape Unit	Pool of potential native species				Vegetation cover	Riparian corridor	
Segment	Enviromental filters	Mean channel slope		Gravels	Channel Dynamism	Guild structure	Pioneer vs. mature communities
Reach	Enviromental filters	Lentic & lotic species	Lithal & Psammal & Pelal	Akal	Siltation tolerant species	Schredders, collectors and scrapers	Pioneer or Mature community
Geomorphic Unit	Local species Pool	Shear stress Boundary layer	Lithal or Psammal or Pelal	Akal	Siltation tolerant species	Schredders, collectors and scrapers	Pioneer or Mature community

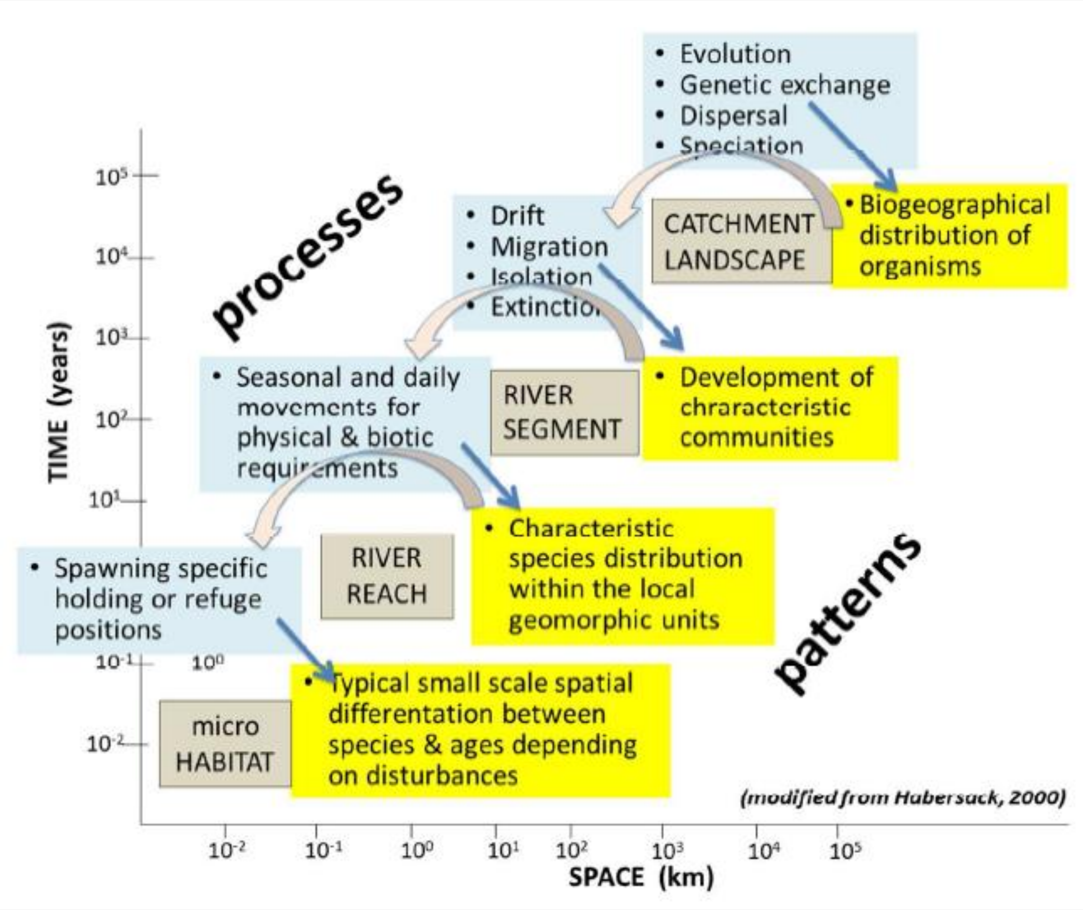


Figure 3.8 Biotic processes and patterns at various scales: the boundary conditions for units at a certain scale are given by processes acting at larger scale (from Garcia de Jalon et al., 2014).

III. Fish

The main hydromorphological controls on fish community are:

(i) *Climate*, at the region scale. Together with biogeography and history of natural dispersal and adaptation, it influences the long terms changes in community composition.

(ii) *Land use* (and related changes), at catchment scale. It influences the amount of fine sediment within the channel at smaller spatial scales, which may cause siltation of interstices between bed sediment particles, and consequent change in community composition (favouring species with low oxygen demand).

(iii) *Longitudinal continuity* (and barriers to longitudinal continuity), from catchment (mainly for migratory species), through landscape unit (by limiting genetic exchange also for not migratory species) until the segment scale (potential impact on all fish species).

(iv) *Habitat heterogeneity* (and loss of habitat heterogeneity), at several spatial scales. Fishes display several habitat uses. In general the reach scale represents the home range of a fish species, but they can move within a segment where it can be found a sustainable population of a species. Indeed the segment corresponds to the scale of the functional process zone, i.e. the fish region. Additionally, some migratory species need an entire river network in order to complete their life cycle.

- At the landscape unit and segment scales, habitat heterogeneity displays through the presence of different river types along the river network which can host different fish communities with specific adaptations to different fluvial disturbances (e.g. more steep and fast water segments versus more gentle and slow water segments; single-thread versus multi-thread patterns; more stable versus more dynamics segments and reaches) (Figure 3.9). Indeed, fish species developed several life cycle adaptations to natural disturbance, mainly floods and droughts (e.g. high fecundity, multiple or protracted spawning, delayed migration). The assemblage of fishes along segments corresponds to the species' preferences of specific habitat conditions (at the reach scale within segments).
- At the reach scale, habitat heterogeneity means a complex mosaic of diverse flow patterns, sediment and habitat structures, in terms of geomorphic and hydraulic units. The presence of various habitats support different life stages as well as different daily habitat uses (feeding zones, spawning zones, refuges, etc.). Lateral continuity with the floodplain is also important during floods at the reach scale. Reaches belonging to different river types support different assemblages of geomorphic and hydraulic units and thus of fish communities.
- At the geomorphic and hydraulic unit scales, local conditions in terms of sediment, flow patterns, presence of aquatic vegetation support different habitat uses by fish species.

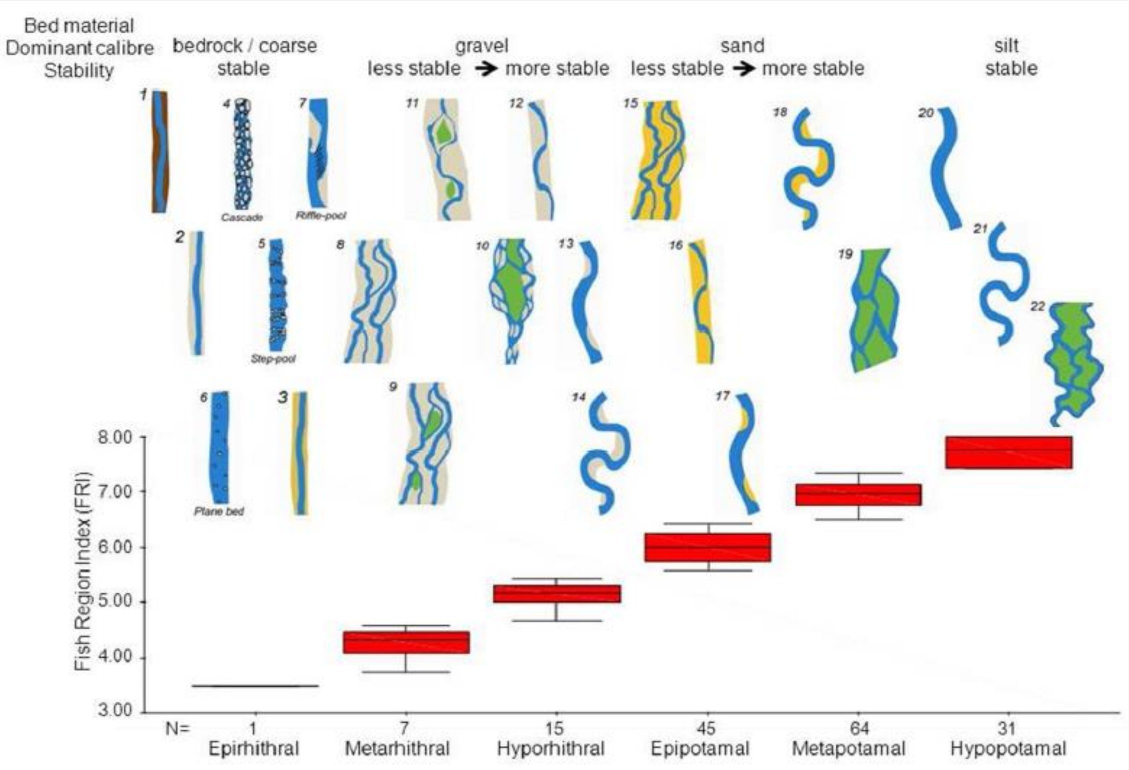


Figure 3.9 Approximate correspondence between river types (according to Gurnell et al., 2014) and the species-specific Fish Region Index (from Wolter et al., 2015). N= number of species, classification according to Wolter et al. (2013).

Links

- A wider description of the delineation and characterization framework is reported within the REFORM Deliverable D2.1
- Influence of Natural Hydromorphological Dynamics on Biota and Ecosystem Function is widely described within the REFORM Deliverable D2.2

4. Stage II: Assessment of temporal changes and current conditions

Following the catchment-wide delineation, characterization and analysis of the river system (Stage I), this Stage performs a diagnosis of river conditions.

Diagnosis starts from an assessment of past changes, including characterization and interpretation of evolutionary trajectories and causes. Current conditions are then analysed using a series of diagnostic tools to assess the hydromorphological components of the river system, including the hydrological regime, the morphological conditions, the riparian vegetation, and geomorphic units.

The final step of this Stage consists of monitoring current hydromorphological conditions, i.e. carrying out periodic measurement of parameters or indicators to assess if changes are occurring relative to an initial condition.

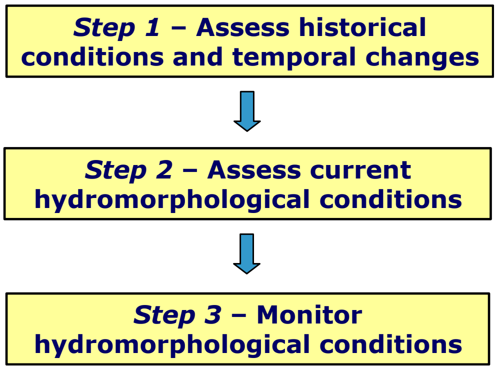


Figure 4.1 Steps of the Stage II.

4.1 Step 1: Assess historical conditions and temporal changes

This section provides an overview of practical tools, measurements, parameters, data representations and interpretations which are used to assess historical conditions and temporal changes, with a particular focus on identifying channel adjustments and evolutionary trajectories over a time scale that is meaningful when interpreting current river conditions (about the last 100 – 200 years).

Basic Questions of Stage II - Step 1

- What were the *conditions* of the catchment, floodplain, and channel in historical times?
- What was the *river morphology* in historical times?
- Which *human and natural factors* have influenced flow regime, sediment supply and transport, and channel morphology?
- Was the river channel *stable* in historical times or did *morphological changes* occur (bed elevation, cross section, channel pattern)?
- What has been the *trajectory* of channel and floodplain changes, and the *rates of change* in channel and floodplain characteristics?
- What are the contemporary trends of *current adjustments*? Is the river continuing to change in the same direction as in the past, has it stabilised, or is it reversing its evolutionary trend?
- What have been the *causes* of recent changes, and have any responsible *human pressures* changed over time?

Four main types of information source can contribute to the assessment of historical conditions and changes in a river system: (1) Field survey; (2) Remote sensing; (3) Historical data; (4) Palaeo data. These were reviewed in detail in D2.1 and can be used to derive information on changing hydromorphological characteristics at different spatial scales. A summary of methods for analysing temporal change at each spatial scale is provided in Table 4.1.

Table 4.1 Main approaches and methods to analyse temporal hydromorphological changes at different spatial scales.

Spatial Scale	Characteristics	Main approaches and methods
Catchment / Landscape unit	Land cover / use	Aerial photography, satellite imagery and land surveys, GIS analysis, palaeo-ecological techniques
	Land topography (Tectonic / Seismic activity, Mass movements)	Surface elevation measurements, identification of mass movements (remote sensing, LIDAR)
	Rainfall and groundwater	Hydrological monitoring records
Segment	River flows and levels	River gauging stations
	Sediment delivery	Field survey and geomorphological mapping, remote sensing and DEMs, palaeo approaches
	Sediment transport	Sediment transport monitoring records, volumetric change in bed topography from aerial photos or DEMs
	Valley setting (gradient and width)	Geomorphological survey, remote sensing, historical topographic maps
	Channel gradient	Historical sources (longitudinal profiles or cross-sectional surveys)
	Riparian corridor and wood	Remotely-sensed data, GIS analysis
Reach	Channel planform, migration and features	Remotely-sensed data, historical maps, GIS analysis, palaeo approaches
	Channel geometry	Cross-sectional topographic survey, LIDAR, Terrestrial Laser Scanning, aerial photographs and multi / hyper spectral data, interferometric or multibeam sonar
	Bed sediment calibre	Field survey

4.1.1 Historical changes in controlling variables

The concept of an evolutionary trajectory of river channel adjustment (e.g., Brierley et al., 2008; Dufour and Piégay, 2009) reflects the fact that a river is a complex system that continuously adjusts its morphology in response to changes in boundary conditions, such as changes in water and sediment fluxes. Each river may exhibit particular adjustment characteristics that are determined by its historical evolution in response to human factors or particular sequences of events. As a result, river-specific interpretation of temporal changes in morphology is essential if current conditions and possible future scenarios are to be correctly interpreted.

This first part of step 1 identifies major changes in controlling variables (e.g., factors influencing flow and sediment transport) that may have determined changes in the river conditions over recent centuries (Table 4.2) at catchment to segment scales. These changes can be investigated using a variety of historical sources (e.g. maps, surveys, documentary evidence, human records, inventories of interventions and management practices) including remotely sensed data such as aerial photography archives which often date back to the mid 20th century.

Table 4.2 Possible changes in controlling variables and methods of investigation.

Type of change	Relevance	Methods
Land cover / use	Historical changes in land cover / use are an important factor influencing key processes at catchment scale such as rainfall – runoff relations, soil erosion, coarse and fine sediment production.	Aerial photos, satellite imagery (e.g. the CORINE land cover map), and land surveys.
Hydrology	Changes in rainfall characteristics and flow regime may alter effective discharge and, therefore, channel morphology.	Hydrological monitoring records, such as precipitation and river flow time series from river gauging stations.
Sediment sources and delivery	May affect sediment transport / channel storage and, therefore, channel morphology. Such changes may be related to natural variations (e.g. climate changes) or human factors (changes in land cover / use, dams, sediment mining).	Geomorphological mapping, landslide inventories, multitemporal analysis of sediment sources by remote sensing, sediment transport monitoring records, inventories of transverse (blocking or bridging) structures and sediment removal from the channel.
Riparian corridor	Riparian corridor characteristics can be influenced by land use in the floodplain, population density, agricultural and management practices (e.g., grazing, vegetation cutting, wood removal). These factors may significantly affect sediment and wood delivery, and thus channel pattern and adjustments.	Remote sensing (aerial photos, satellite imagery) and GIS mapping.

4.1.2 Historical trends of morphological change

As in the analysis changes in controlling factors, the analysis of changes in channel morphology typically focuses on the last 100 – 200 years (Surian et al., 2009); a period that is sufficiently long to provide understanding of current processes to inform river management and restoration strategies, including information on some ecologically relevant processes (e.g., disruption of lateral continuity of flows by channel bed incision). Nonetheless, analysis of channel changes has sometimes considered larger periods of time (e.g., Arnaud-Fassetta, 2003; Uribelarrea et al., 2003).

This type of analysis is particularly relevant to alluvial channels, as their form can change substantially over time. However, alluvial confined or semi-alluvial streams can also show sufficiently large morphological changes that they may also be explored using the following methods.

Bed elevation and cross-section changes

The term "longitudinal profile" refers to a graphical 2D representation of bed morphology, where bed elevation is plotted against longitudinal distances downstream along the channel. Bed elevation can refer to the deepest point in the channel (*minimum bed elevation* or *thalweg*) or, alternatively, to the *mean bed elevation* (see cross-section parameters).

The term "cross-section" refers to a graphical 2D representation of channel morphology that is perpendicular to the flow direction along which distances and elevations are surveyed and then plotted. Cross-sectional surveys provide data for the analysis of channel width and depth, wetted perimeter, bank height and angle, and the presence, elevation, and extent of floodplain and adjacent terraces. Derived attributes channel cross-sectional area, average depth, hydraulic radius, and width to depth ratio.

To calculate cross-section parameters, it is necessary to refer to a given flow stage (the bankfull stage is often used as the reference elevation), and this reference stage is then used to measure channel properties such as maximum or mean depth. *Maximum depth* is the difference between the reference stage and minimum bed elevation (thalweg), while *mean depth* is the difference between the reference flow stage and mean bed elevation or the ratio of cross-section area to channel width. *Mean bed elevation* is the average elevation of the channel bed recorded between the toe of each bank (banks are generally excluded from this calculation).

The main methods used to characterise and quantify bed elevation and cross-section changes are summarised in Table 4.3.

Table 4.3 Main methods for characterising bed elevation change.

Methods	Description
Superimposition of existing topographic surveys of longitudinal profiles of bed elevation	Superimposed bed profiles or minimum bed elevations extracted from cross-sections are used to identify the direction and amount of changes (Simon et al., 2015)
Superimposition of existing topographic surveys of channel cross-sections	Historical series of cross-sections allow investigation of changes in cross-section parameters such as channel width, depth, width-to-depth ratio, and whether net erosion or deposition has occurred (Murphey and Grissinger, 1985; Simon, 1992; Petit et al., 1996; Martín-Vide et al., 2010)
Gauged water level / discharge analysis	Identification of water level changes associated with specific, fixed discharges, indicate possible bed level or channel width changes ('specific gage analysis', Wilson and Turnipseed, 1994; Jacobson, 1995)
Field evidence	(a) Exposure of bridge piles or other structures; (b) differences in elevation between geomorphic surfaces (e.g., historical vs. modern floodplain, Rinaldi, 2003; Liébault et al., 2013)

Representation of temporal changes in bed elevation and cross-section parameters can be achieved in two ways (Figure 4.2): (1) multi-temporal longitudinal profiles, and (2) at-a-site bed-level changes.

Multi-temporal longitudinal profiles provide direct information on the spatio-temporal distribution of changes, and capture temporal changes in bed slope (e.g. Rinaldi & Simon, 1998). However, whether based on surveyed long profiles, or interpolation between cross sections, various sources of error may significantly affect the apparent changes that are identified, including the absolute accuracy of old surveys, the elevation datum used for each profile, and identification of common reference points. Furthermore, the distances along the river channel incorporated in the long profile may change due to variations in the planimetric position of the channel through time. In this case, some common points need to be identified along the longitudinal profiles (e.g. bridges or other fixed structures), so that distances between these common points can be corrected.

At-a-site bed-level changes obtained by plotting bed-elevation (or minimum annual river stage) through time, provide detailed information on the temporal trend or trajectory of change at a single site and allow identification of phases of adjustment (which may vary among sites).

Interpretation of temporal trends can be supported by fitting mathematical functions through the observed data. In unstable channels, bed elevation changes through time (years) are generally best described by nonlinear functions, where response to a disturbance occurs rapidly at first and then slows and becomes asymptotic to a new condition or level. Mathematical forms that have been found to be suitable for describing at-a-site bed level adjustment with time, and to predict future bed elevations include exponential, power, and hyperbolic functions (e.g. Graf, 1977; Williams & Wolman, 1984; Simon 1989; Wilson and Turnipseed 1993; 1994; Rinaldi & Simon, 1998; Simon & Rinaldi 2000).

The main problems that arise when using historical cross-sections are mainly related to the identification of reliable common points among different surveys. The selection of a reference water stage elevation can also be problematic, as bankfull stage in historical sections is often difficult to distinguish. In such cases, changes in the entire cross-section are generally measured with reference to the maximum water stage that can be contained within the channel.

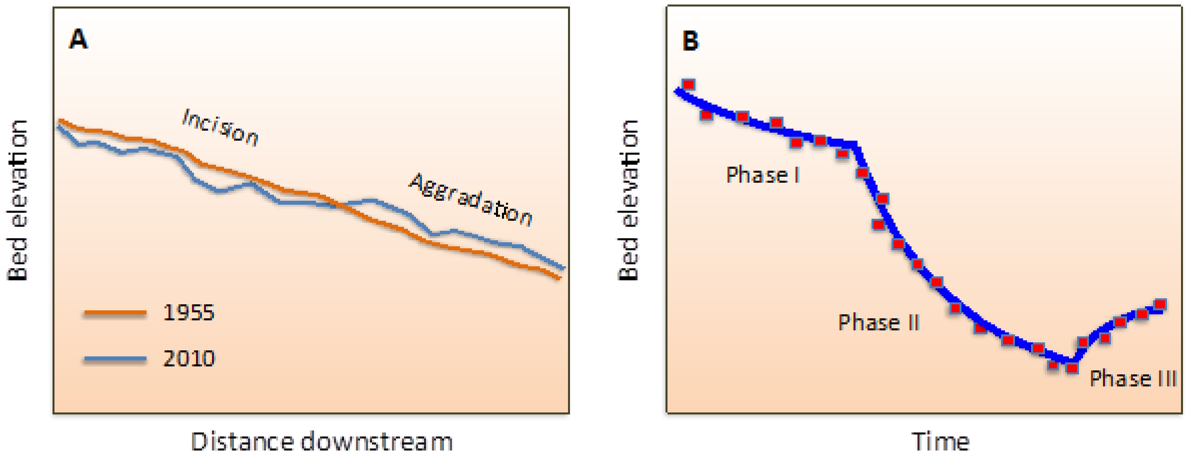


Figure 4.2 Representation of bed elevation change. (A) Multi-temporal longitudinal profiles; (B) bed-level changes at-a-site.

Planimetric changes

Planimetric changes include changes in channel planform, position, geomorphic units and vegetational features within the channel and the floodplain. Channel planform refers to the 2D planimetric character of the channel. Measurements that describe channel planform include channel width, depth, area; the number of active channels; sinuosity, braiding and anabranching indices; meander belt width, amplitude and wavelength: and the radius of bend curvature. The rate of channel migration is widely used to describe changes in channel position. Furthermore, planimetric changes in geomorphic units within the river channel (e.g. number and extent of bars, islands, etc.) and river corridor (e.g. floodplain units, vegetation properties) are also relevant descriptors of channel changes.

These measurements are mainly obtained for alluvial channels, which have the ability to adjust their planform in response to interactions between driving variables (i.e. water and sediment flow) and channel boundary characteristics, since the planform and dimensions of bedrock channels are strongly constrained by geological and structural factors.

A summary of the main methods used to characterise and quantify channel planimetric changes is presented in Table 4.4. The use of historical maps, aerial photos, and other remotely sensed data sources allows analysis of spatio-temporal trends in many of the previously defined planimetric parameters to reveal temporal changes in channel configuration. However, it is important to quantify errors resulting from the quality, resolution, colour, scale, and geocorrection of such sources, which can significantly affect the apparent changes that are identified (e.g. Mount et al., 2003; Gurnell et al., 2003; Hughes et al., 2006; Lane et al., 2010; Magdaleno and Fernández-Yuste, 2011a; Swanson et al., 2011).

Table 4.4 Methods for characterising planimetric changes of river channels and corridors.

Methods	Description
Historical maps	Old maps (16th to 19th century) can provide qualitative information but are often useful to assess the channel planform and position, and to understand types and locations of human interventions. More recent maps (late 19th century to present) that use consistent mapping conventions can be used to quantify channel planform adjustments (Petts et al., 1989; Gurnell et al., 2003).
Aerial photographs	Aerial photos obtained at quasi- decadal intervals are ideal for quantifying planform changes, channel migration rates, and changes in geomorphic units over time. Information can be digitised from photographs (and recent maps) of various scales and then registered to a common scale and projection within a GIS, to permit direct comparison and analysis (Gilvear and Bryant, 2003; Gurnell et al., 2003).
Satellite images	increased with the improvements in spatial, temporal and spectral resolution, and several decades of records are now available for some platforms (Bizzi et al., in press).

Similar to bed-elevation data, representation of planimetric parameters is generally presented in two ways: (1) spatio-temporal distributions are achieved by plotting the parameter against distance downstream for different years; and (2) temporal trends are revealed by plotting the mean value of the parameter for a given reach against time. The first type of representation visualises the spatial variation of a given planimetric parameter and compares values at the same position in different years. The second type of representation provides information on the temporal trend, or trajectory, of the parameter, and is usually presented at the reach-scale.

The parameter that is most frequently used for analysis of planimetric changes is channel width (or "active" channel width) (Figure 4.3), i.e. the distance between the channel margins that enclose baseflow channels and depositional bars. Temporal trends in the sinuosity index can verify whether changes in morphological pattern has occurred (e.g. from sinuous to meandering). Historical trends in braiding intensity are also extremely useful for investigating changes in channel pattern (Gurnell et al., 2009), although greater uncertainty is associated with this parameter because it is influenced by water stage, so, as far as possible, analyses should be applied to photographs captured at times of similar water level.

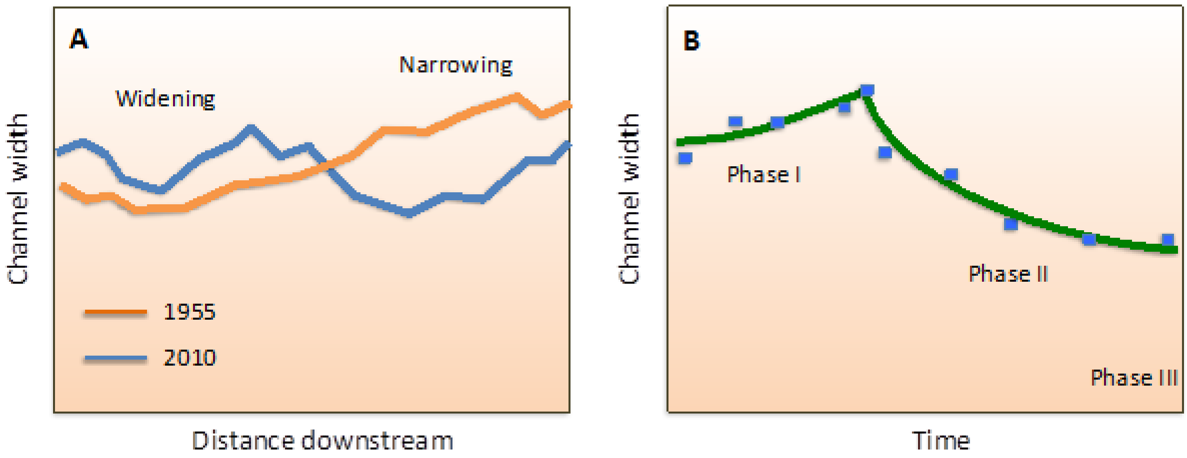


Figure 4.3 Change in channel width. (A) Spatio-temporal changes; (B) reach-scale temporal trend.

4.1.3 Contemporary changes

Analysis of recent channel changes (e.g. 10 – 20 years) identifies ongoing trends of adjustment and contemporary instability processes, which may differ from those identified over historical time scales. For example, a river which has lowered its bed elevation during the last 100 years may show bed aggradation over shorter time periods, whether or not the long term trend is undergoing an adjustment or reversal. While historical changes are important for understanding the longer-term influences on current processes and morphological conditions, assessment of contemporary changes (10 – 20 years) can be very informative when making predictions of possible future trends, particularly at decadal time scales. In relation to both long- and short-term changes, it is important to consider how these may be influenced by adjustments in surrounding reaches and also by controlling processes generated from larger spatial units.

Methods and approaches to assessing recent channel changes (last 10 – 20 years, Table 4.5) do not differ greatly from those reviewed in the previous section, except that the relative utility of different source types changes.

Table 4.5 Main methods for analysing contemporary morphological changes.

Methods	Description
Topographic survey	Repeated topographic surveys are used to measure longitudinal profile, bed elevation, cross-sectional changes, bank retreat with increasing precision and spatial resolution associated with new survey techniques (GPS, Terrestrial Laser Scanning, etc.) (e.g. Pyle et al. 1997; O'Neal and Pizzuto 2007, Grabowski et al., 2014).
Remote sensing	Aerial photos, satellite images, or LiDAR are preferred for measuring planform changes, rates of channel migration, and morphometric changes of geomorphic units e.g., Notebaert, 2009; Marcus and Fonstad, 2010; Legleiter, 2012).
Field survey	Can be crucial to gaining information on recent changes and ongoing trends of adjustment, especially where other information sources are not applicable (e.g., remote sensing in case of small streams) or where other data are not available. The main types of field evidence are summarised in Table 4.6.

Table 4.6 Main types of evidence and indicators used during field survey to assess contemporary change.

Type of change	Geomorphic units /features and other types of evidence
Bed incision	(i) Recent terraces; (ii) nickpoints; (iii) narrow and deep channel cross profiles; (iv) bank failures and undercutting on both banks; (v) bed sediments (e.g. gravel (overlain by finer true bank material) exposed in banks above current bed level; (vi) trees collapsing / leaning into channel on both banks; (vii) dying riparian vegetation, or root zones well above the low flow water surface; (viii) compacted, armoured bed and bed coarsening; (ix) exposed foundations of new structures such as bridge piers.
Bed aggradation	(i) Buried soils (often revealed in bank profiles); (ii) burial of coarser bed material by deep finer sediment; (iii) in-channel deposition of fine sediment or poorly sorted sediments; (iv) widespread loose, uncompacted bars; (v) burial of recent structures and contracted channels relative to bridge openings; (vi) partial burial of established vegetation (visible around old stems).
Channel narrowing	Active lateral channel accretion and vegetation encroachment on opposing banks (stabilizing, vegetated bars or benches on both banks), or presence of wide benches opposite to non-eroding banks.
Channel widening	Active channel erosion (unreinforced banks with vertical, vertical-undercut, vertical with toe profiles) is observed on both (opposing) banks.
Channel stability	(i) Well vegetated banks and bars; (ii) mature trees on both banks; (iii) negligible active bank erosion.

4.1.4 Interpret morphological changes and their causes

The final part of step 1 interprets and classifies the trajectory of morphological change, and identifies possible influences on this trajectory.

Observation of channel changes does not necessarily imply channel instability. The distinction between *'dynamic equilibrium'* and channel *'instability'* is based on the spatial and temporal scales of morphological changes, and on their impact on channel geometry, gradient, or pattern (Table 4.7; Figure 4.4).

Table 4.7 Main differences between dynamic equilibrium and instability.

Dynamic equilibrium	Instability
Definition	
A river may be highly dynamic but also geomorphically stable (i.e., in a state of dynamic equilibrium) if its long-term (i.e., 10 years or more) temporal average properties (channel width, depth, slope, sediment input and output) are stationary (Shields et al., 2003)	A river reach can be considered as unstable if it exhibits abrupt, episodic, or progressive changes in location, geometry, gradient, or pattern because of changes in water or sediment inputs or outputs (Rhoads, 1995; Thorne et al., 1996)
Spatial and temporal scales	
Short-term, event-related, localized (site or sub-reach scale)	From the reach-scale to the entire alluvial system and within a significantly long temporal scale (at least 10 – 15 years)
Processes	
Scour; fill; localised lateral changes	Bed-level adjustments (incision or degradation, aggradation); changes in channel width (narrowing, widening); widespread lateral changes (channel migration, avulsion); changes in channel pattern (or type)
Overall cause	
Localised alteration of channel geometry, transport capacity or sediment supply	Alteration of the driving variables (water and sediment discharge)

A final task is to investigate the possible *causes* of channel changes within the catchment context, which may have influenced the evolutionary *trajectory* (Figure 2.2). Various types of controlling variables influencing a trajectory of change can be distinguished (Dufour and Piégay, 2009), including: (1) progressive (e.g., climate or land use change); (2) impulsive (e.g., floods); (3) discontinuous or transient disturbance (e.g., sediment mining) or a permanent intervention (e.g., dam, bank protections). It is also important to discriminate the spatial scale at which controlling factors operate, particularly distinguishing between those that operate at the catchment or landscape unit scale (e.g., land use change) and those that operate the segment or reach scale (e.g., dams, bank protection, sediment mining, etc.). Furthermore, it is important to identify the existence and eventually the exceedance of geomorphic thresholds and their relative causes (e.g., causes of a change from a multi-thread to a single-thread channel).

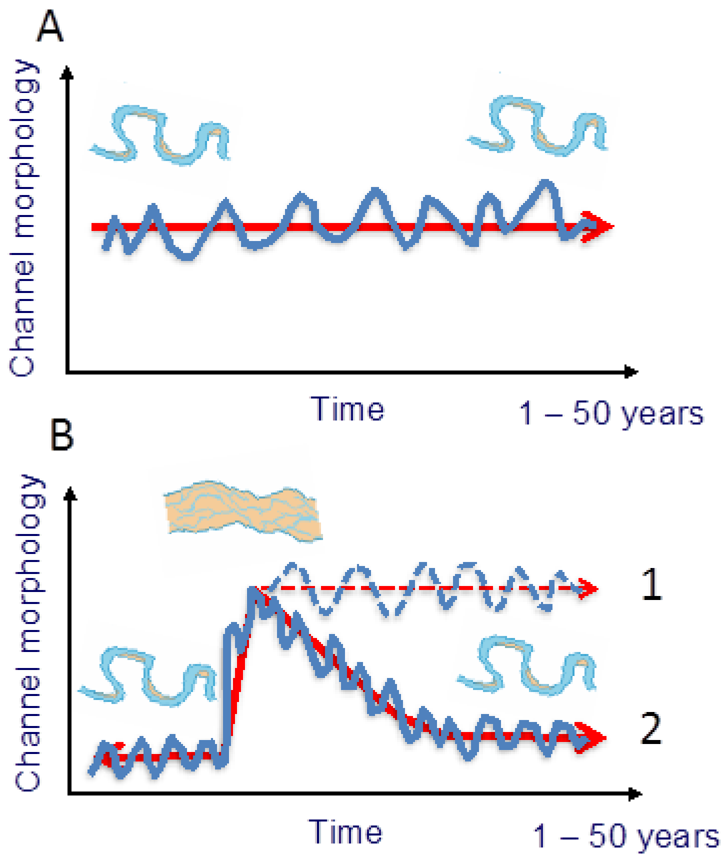


Figure 4.4 Dynamic equilibrium and instability (modified from Sear et al., 2010). (A) Dynamic equilibrium: channel in equilibrium with water and sediment load; minor morphological change (scour/fill). (B) Instability and threshold effects. 1: No return to original state – morphology changed to new equilibrium; 2: Adjustment to previous equilibrium.

Construction of a *chronology* or *time-chart* helps to visualise the changes that have occurred in the catchment, landscape units, river corridor, and channel over time (e.g. Sear et al., 2010; Downs et al., 2013) by synthesising changes and their potential causes (e.g. Figure 4.5). The chronology synthesises the available information on the possible factors influencing hydromorphological processes (e.g. changes in land cover, riparian vegetation, human interventions, channel discharge, major flood or drought events) and channel responses (e.g, planform pattern, channel position and dimensions).

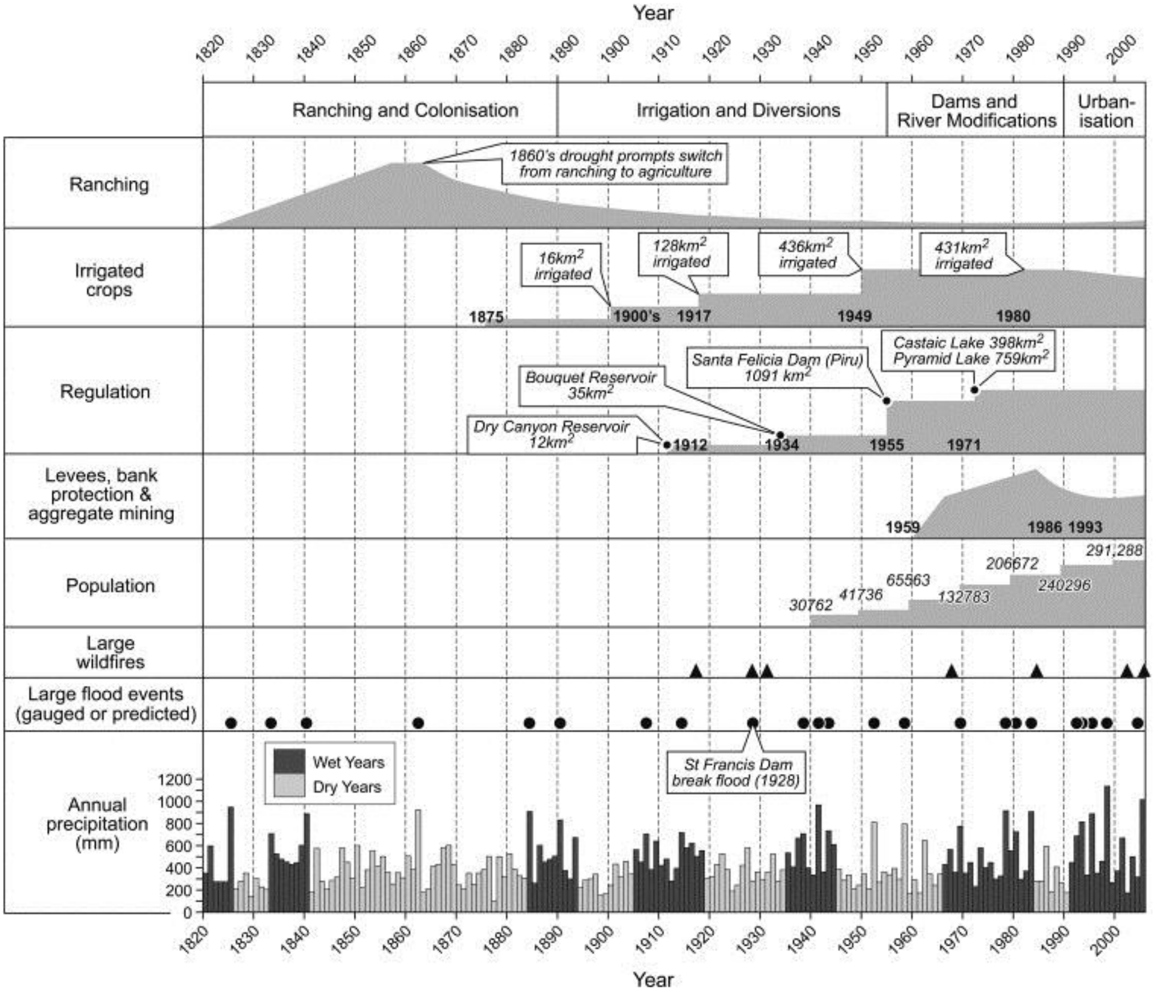


Figure 4.5 A chronology is a valuable tool to integrate data sources, track changes in hydromorphological characteristics over time and explore causal linkages (from Downs et al., 2013).

Box 4.1: Channel adjustments in European rivers

Several studies have documented channel adjustments occurred in many areas of Europe, including France (Liébault and Piégay, 2001, 2002; Liébault et al., 2013; Belletti et al., 2015a), Poland (Wyżga, 1993, 2001a, 2001b, 2008; Zawiejska & Wyżga, 2010), Italy (Rinaldi and Simon, 1998; Rinaldi, 2003; Surian and Rinaldi, 2003; Surian et al., 2009; Bollati et al., 2014; Scorpio et al., 2015), Spain (Garcia-Ruiz et al., 1997; Rovira et al., 2005; Ollero, 2007; Magdaleno & Fernández-Yuste, 2011b), United Kingdom (e.g. Gurnell et al., 1994; Large and Petts, 1996; Gurnell, 1997; Winterbottom, 2000), Norway (Fergus, 1997), and Austria (Hauer and Habersack, 2009). Most of these studies have demonstrated similar trends of channel adjustments (Rinaldi et al., 2013a). These have included an early, historical period characterised by aggradational processes affecting different components of the fluvial system (alluvial plain, channel bed, delta), followed by a reversal of the general aggradational trend in the late 19th century and 20th century as a result of various types of human disturbances (Petts et al., 1989; Łajczak, 1995; Bravard et al., 1997) and widespread hillslope reforestation and upland sediment retention, against a background of climate changes following the end of the Little Ice Age. These trends have been observed in many parts of Europe, including the piedmont areas of mountain (Liébault and Piégay, 2002; Comiti, 2013) and Mediterranean (Hooke, 2006) regions.

Despite the occurrence of different types of disturbances, common channel responses have been observed during the 20th century in many areas, with two dominant types of morphological adjustments being channel incision or aggradation coupled with narrowing (Figure 4.6 and 4.7 illustrates incision and narrowing trends observed in much of central and southern Europe).

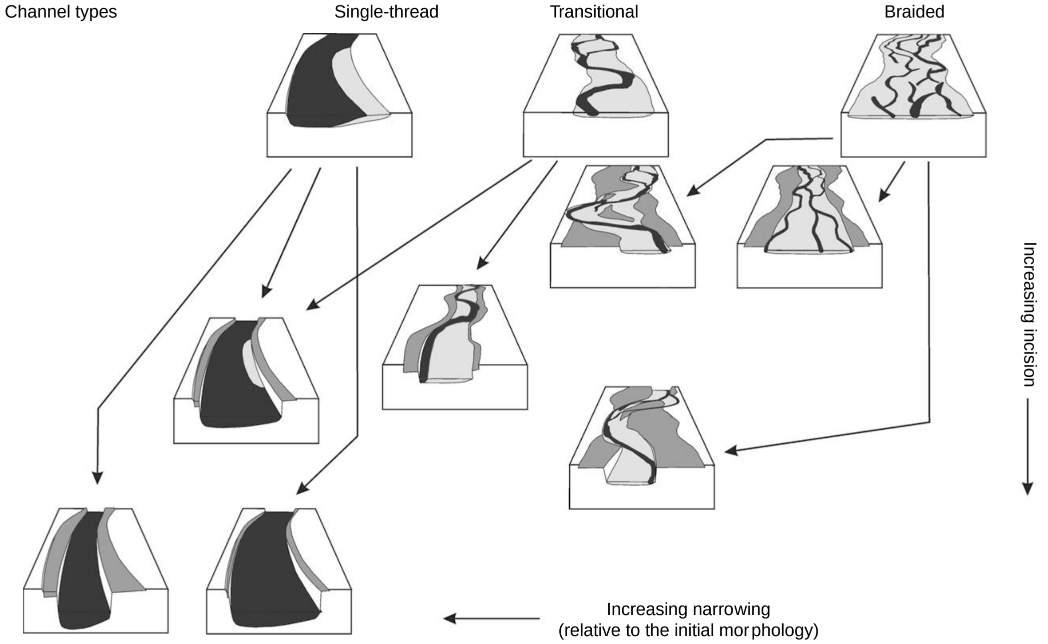


Figure 4.6 Summary of main types of channel adjustments in Italian rivers during the past 100 years. Starting from three initial morphologies, different channel adjustments were observed according to variable amount of incision and narrowing (modified from Surian and Rinaldi, 2003).

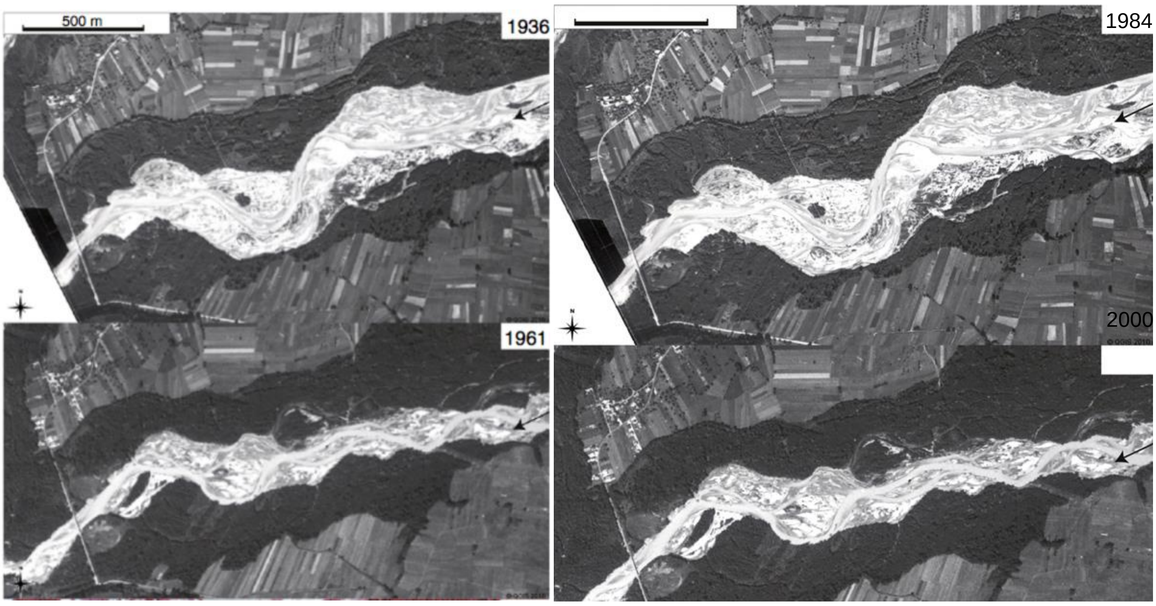


Figure 4.7 Corridor evolution from 1937 to 2000 of the Arve River (tributary of the Rhône River, France). Watershed land-cover changes, dams, embankments, and gravel-mining-generated channel metamorphosis from a braided to a single-thread channel morphology (from Rinaldi et al., 2013a). Source: IGN.

In most cases, these responses have been attributed to alterations in sediment fluxes or sediment mining (Liébault and Piégay, 2002; Surian and Rinaldi, 2003; Grabowski and Gurnell, 2014), but where upstream progression of channel changes have occurred, channelization and a resultant increase in the river's transport capacity have been implicated (Wyżga, 2008).

In some cases, different phases of channel adjustments have been recognized. For example, in Italy many alluvial channels underwent two phases of narrowing and incision, which started at the end of the nineteenth century (phase I), and from the 1950s to the 1980s (phase II) (Figure 4.8). Then, over the last 15–20 years, channel widening and aggradation have been observed along parts of the reaches (phase III), while a continuation of the previous phase of incision and narrowing was also observed in other cases (Surian et al., 2009).

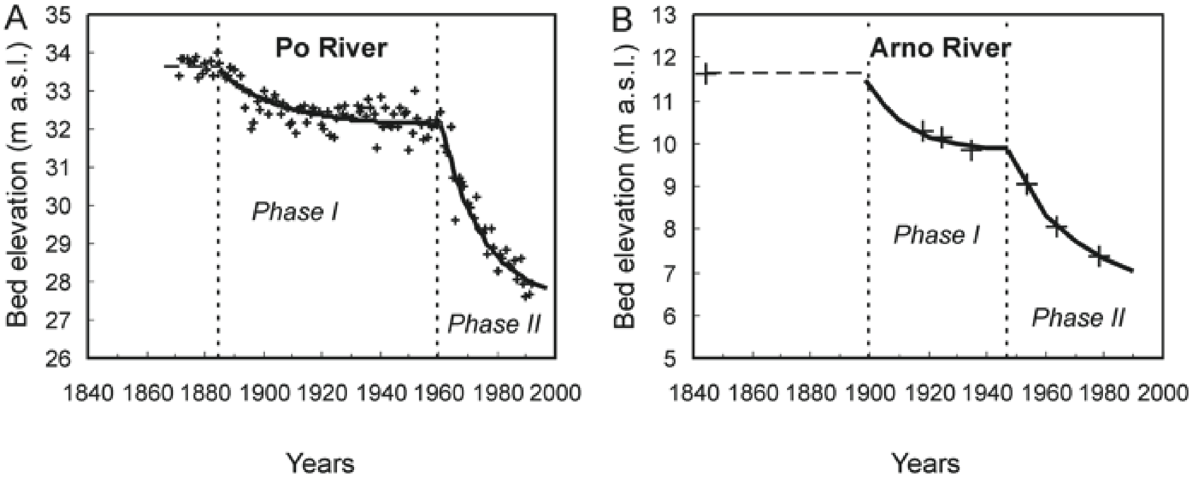


Figure 4.8 Bed-level adjustments at-a-site and identification of phases of bed changes (from Surian and Rinaldi, 2003): examples from (A) Po River (minimum annual river stage at the gauging station of Cremona), and (B) Arno River (minimum bed elevation extracted from cross-sections of different years).

Main Outputs of Stage II - Step 1

- Summary Tables of the main natural factors and human disturbances influencing catchment, landscape unit, segment to reach floodplain and channel conditions in historical times
- Graphs representing the evolutionary trajectories of the main morphological parameters (e.g., channel width, bed elevation, etc.)
- Summary Tables and/or GIS maps of channel changes
- Chronology or time-chart for visualising changes that have occurred in the catchment, landscape unit, segment to reach floodplains, and river channels over time

4.2 Step 2: Assess current hydromorphological conditions

The second step of Stage II assesses current conditions, based on the knowledge of past changes. Hydromorphological assessment consists of a suite of methods and procedures that identify and characterize hydromorphological features in order to evaluate river conditions. Assessment conducted during this stage differs from the characterization of spatial units performed in Stage I because it implies some degree of evaluation and judgement of the conditions or state (e.g., good, poor, etc.) of the river.

Basic Questions of Stage II - Step 2

- Which are the *critical reaches* within the catchment where a detailed assessment should be concentrated?
- Have alterations of the hydrological regime occurred? What are the causes? What is the *hydrological state* (good, moderate, poor) of the investigated river reaches?
- Have morphological alterations occurred? What are the causes? What is the *morphological state* (good, moderate, poor) of the investigated river reaches?
- Have alterations occurred in the riparian vegetation? What are the causes? What is the *state of the riparian vegetation* (good, moderate, poor) along the investigated river reaches?
- What are the assemblages of channel and floodplain *geomorphic units* along the reach? Is there any indication that human disturbance has altered the types of geomorphic units along the reach? Is there any evidence for evolutionary adjustments of river type which may have caused any discernible change to the assemblage of geomorphic units?

Many hydromorphological methods have been developed. They vary widely in their underlying concepts and aims, spatial scale, indicators and collected data. According to REFORM Deliverable 1.1, five broad categories of assessment methods exist based on their main focus and objectives (Table 4.8). Initially, hydromorphological assessment was assimilated into physical habitat assessment methods (e.g. Platts et al. 1983; Raven et al. 1997, 2002), and also there have been attempts to standardise these habitat-based methods through the CEN (2004) guidance, providing a protocol for 'recording the physical features of rivers', and the CEN (2009) concerning the determination of the degree of modification of river hydromorphology. However, over the last decade, it has been recognised that a broader 'river condition assessment' is needed that goes beyond an inventory of physical habitats to include the assessment of "pressure" or "response" variables with a stronger emphasis on river dynamics and processes (e.g. Fryirs et al., 2008).

Table 4.8 Definition of categories of assessment methods.

Category of methods	Definition
Physical habitat assessment	Methods used to identify, survey and assess physical habitats
Riparian habitat assessment	Physical habitat assessment methods specifically developed for characterizing and assessing riparian habitats and vegetation
Morphological assessment	Methods performing a geomorphological evaluation of river conditions, including morphological characteristics and/or human pressures on hydromorphology
Assessment of hydrological regime alteration	Methods specifically used to assess the deviation of the hydrological regime from unaltered conditions.
Assessment of fish longitudinal continuity	Methods specifically developed to evaluate the alteration of the longitudinal continuity of rivers for fish communities related to human barriers.

Box 4.2: Recommendations for the application of assessment methods

Based on the comprehensive review on existing methods for hydromorphological assessment, some recommendations for the application and for future development of these methods have been provided (Belletti et al., 2015b).

- Most of the methods currently used to assess hydromorphology focus on the occurrence and spatial configuration of **physical habitats**, using a limited spatial scale of investigation (i.e., the site scale of a fixed length of few 100 m) and with a tendency to consider fluvial features in a static way, rather than placing them in the temporal context within which channel processes operate and river channels adjust. Consequently, these methods are generally inadequate when they are used with the aim of understanding physical processes and causes of river alterations (e.g. Fryirs et al. 2008).
- It is suggested that future developments need to **incorporate physical processes**. This can be achieved by a wider use and implementation of methods for morphological rather than just physical habitat assessment in order to increase the capability to assess geomorphic processes.
- The assessment of morphological processes and alterations should be undertaken within an appropriate **spatial hierarchical framework** and scaling methodology, emphasizing relevant spatial units and temporal time scales, and identifying key controlling factors at each spatial scale as well as appropriate morphological indicators.
- The use of an **integrated hydromorphological assessment** is recommended, where the morphological and hydrological components (including vegetation as a morphological driver) are key parts of the evaluation and classification of hydromorphological state and quality.
- Such an integrated approach incorporates a range of different scientific skills and disciplines (e.g., hydrology, geomorphology, biology), and **application of each specific approach requires expertise and training**. Application of assessment methods without the necessary background and skill can seriously limit the validity of an integrated analysis of a river system.

4.2.1 Analysis of pressures and initial screening

Application of assessment tools to large numbers of water bodies or to an entire river network is often impractical. An initial screening may be used to identify critical reaches where detailed assessments should be concentrated. While there are many available hydromorphological assessment methods, structured and rigorous initial screening tools are lacking. This is in part related to the difficulty of reconciling the constraints on time and resources with the complexity of a hydromorphological assessment.

The most suitable way to conduct initial screening is to use readily available information on **existing pressures** in the catchment and along the river system, including information on land use, urbanized areas, and a map layer of artificial elements and interventions. **Past pressures** that are not obvious from current conditions (e.g., past land use and its changes, past interventions or removal of existing interventions), based for example on the Step 1 of Stage II, should also be included in the analysis. Information on existing pressures should be embedded into an appropriate **spatial framework**, such as that developed during Stage 1 Step1, at least at a first level of approximation. Identification and delimitation of the main categories of channel types (multi-thread vs. single-thread, meandering vs. straight) can be also useful. In many catchments a clear spatial sequence of alteration is observed moving downstream since human activities and urbanized areas tend to increase along the alluvial plains of lowland areas. Therefore, delimitation of multi-thread or transitional morphologies (e.g., braided, wandering) may become an indirect indicator of alteration of channel pattern, or straight reaches may indicate a strong planimetric artificial control.

GIS-based mapping is very useful for such preliminary assessments, allowing the visualization of areas and river reaches in the catchment where pressures are concentrated (Figure 4.9).

Table 4.9 Types of information required for an initial screening.

Type of information	Description
Main artificial elements	(1) barriers disrupting longitudinal continuity (dams, check dams, abstraction weirs); (2) structures inducing significant hydrological alterations (hydropower dams); (3) reaches crossing urban areas; (4) reaches with high degree of planimetric constraint.
Past pressures	(1) land use change; (2) past interventions or removal of existing interventions.
Main spatial units	(1) landscape units (mountain, hilly or plain areas); (2) river segments with different lateral confinement (confined, partly confined, unconfined); (3) basic river types (multi-thread vs. single-thread, meandering vs. straight).

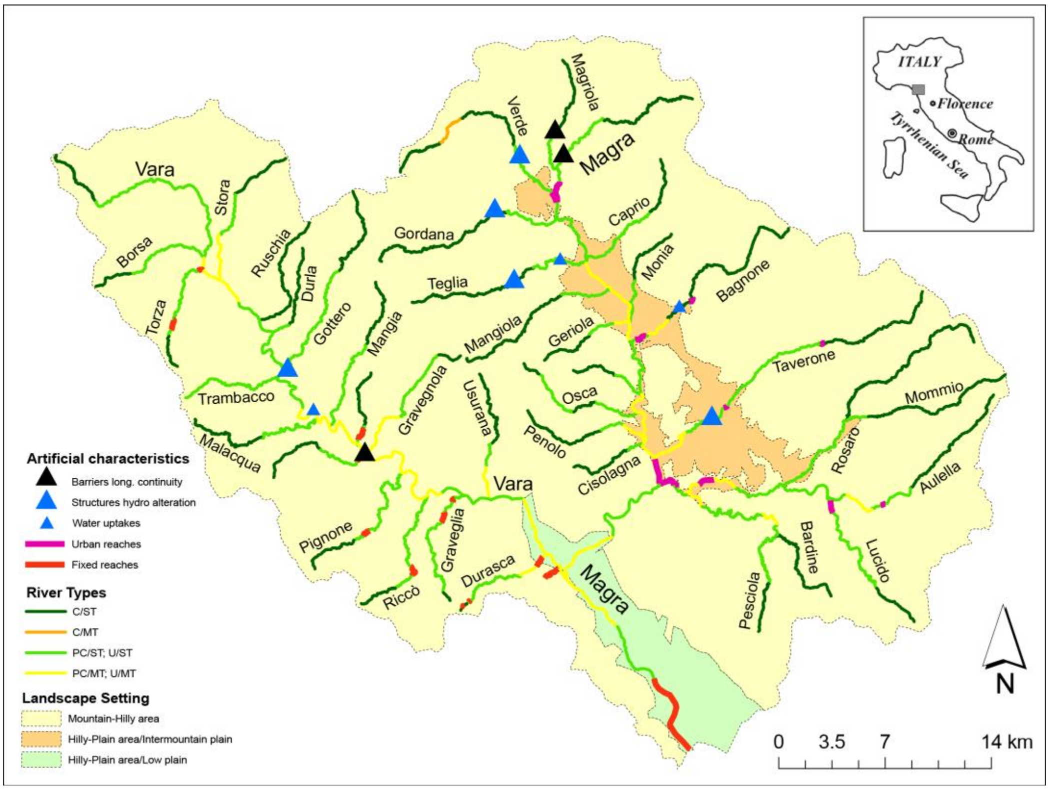


Figure 4.9 Example of GIS mapping of artificial elements and main physiographic features to support an initial screening of critical hydromorphological conditions: application to the Magra River catchment (Italy). River types: C=confined, PC=partly confined, U=unconfined, ST=single-thread, MT=multi-thread.

Box 4.3: Recommendations for the application of screening tools

Screening tools should **not be used as a substitute for hydromorphological assessment**, but rather to provide appraisal of pressures and physical conditions at catchment scale. Potentially altered reaches are not necessarily located where the pressures are concentrated. Channel adjustments in response to pressures migrate over time and space and may affect previously undisturbed reaches which may be distant from existing pressures. Furthermore, channel adjustment processes may determine strong alterations in the hydromorphological functioning of a river (e.g., channel bed incision may disconnect the floodplain or cause bed armouring, etc.).

4.2.2 Hydrological assessment

Hydrological assessment includes methods specifically used to assess the deviation of the hydrological regime from unaltered or previous conditions. Most of the methods used within Europe are based on some or all of the Indicators of Hydrologic Alteration (IHA) proposed by Richter et al. (1996) and Poff et al. (2003). The output of these assessments is usually a synthetic index of the degree of deviation from unaltered conditions.

The main strength of such assessments is that they use robust indicators based on quantitative assessments, statistical analyses or physically-based models. Two examples of methods developed in Europe are briefly illustrated below.

Indice di Alterazione del Regime Idrologico (IARI)
(Index of alteration of the hydrological regime)

Reference
ISPRA (2009)

Description
The IARI method, developed in Italy by ISPRA and based on the IHA methodology (Indicators of Hydrologic Alteration, Richter at al., 1996; Poff et al., 2003), compares undisturbed and altered conditions. The undisturbed conditions are modelled starting from current conditions in the absence of existing pressures. Alternatively, unaltered conditions can be assumed to coincide with those existing before a certain relevant pressure took place (e.g. installation of a dam). In either case a comparison is made between pre-impact or naturalised and current conditions.

The pre-impact reference condition can be defined through statistical analysis of the historical time series of streamflow data (discharge values), to locate the breakpoint that divides the series into two portions, assumed to represent natural (i.e. prior to the pressure that caused the hydrological alteration), and post-impact conditions.

The assessment protocol that is followed is based on data availability: (a) sufficient (at least 20 years of data availability), (b) poor, and (c) no data availability.

The IARI calculation protocol consists of the following three steps:

1. Watershed assessment of pressures on the river segment or reach. This phase identifies those pressures that have altered the flow regime and determine the following conditions: a) no pressure or negligible pressures; b) significant pressures.
2. Application of the quantitative methodology and evaluation of the IARI index;
3. Further assessment in the case of particular issues highlighted in Step 2.

In Step 2, for each of the 33 IHA indicators (see REFORM D2.1, Annex C), the following parameters are calculated: a) the lower and upper quartile of pre-impact streamflow data (i.e. reference conditions that are defined as the *natural flow regime* that would be present under present conditions and in the absence of anthropogenic pressures); the mean (or median) of the 33 IHA indicators of post-impact data series (altered conditions, Fig. 4.10).

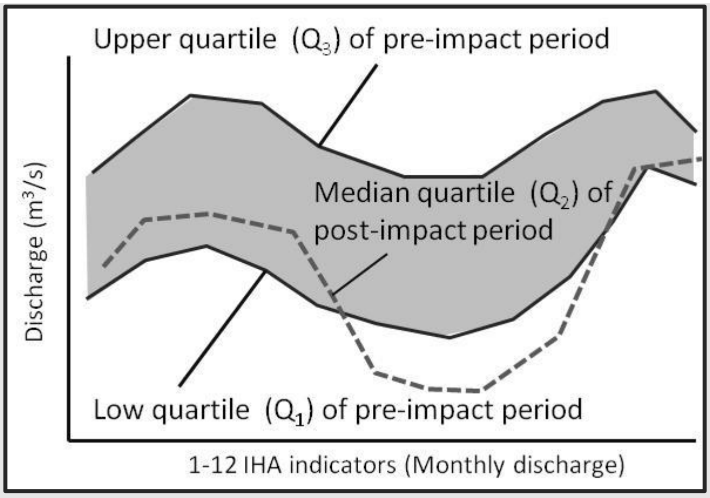


Figure 4.10 Example of the application of IARI methodology (in particular, the first 12 IHA indicators: magnitude of monthly discharge: January - December).

The IARI method provides a comparison between the range of variability of pre-impact conditions and the median values of hydrological parameters during post-impact conditions. As result of the evaluation procedure, three levels of hydrological conditions are defined: *1) High conditions* (no alteration); *2) Good conditions* (average alteration); *3) Not good conditions* (high alteration).

Extension to European level

The method has been implemented for the WFD in Italy and used during the first cycle of RBMPs. The method is incorporated in the REFORM D2.1 framework. It makes use of physically-based indicators that are applicable in different contexts. Therefore there are no particular limitations to using IARI in other European countries beyond Italy.

Indices de Alteración Hidrológica en RIoS (IAHRIS)
(Index of hydrological alteration in rivers)

Reference

Martínez Santa-María and Fernández Yuste (2010); Fernández et al. (2012)

Description

The method, promoted by the then-Ministry of the Environment and Rural and Marine Affairs in Spain, now Ministry of Agriculture, Food and Environment, aims at characterizing and comparing pre-post hydrological conditions, through the calculation of hydrological indicators. It requires monthly or daily data series of at least 15 years in length (not necessarily consecutive).

The method defines 24 indicators (parameters) to be estimated in pre and post impact conditions according to 3 components of the flow regime: (1) habitual regime (7 indicators); (2) flood regime (9 indicators); (3) drought regime (8 indicators). It also considers parameters related to geomorphological aspects such as the "channel forming" discharge. Indicators are weighted according to the mean annual climatic conditions (the method distinguishes between wet, dry, and normal years).

The values of each indicator are then represented in a polar diagram, where two polygons are generated: one representing the reference conditions, and the other representing the actual (altered) conditions. Hydrological alteration is calculated as the deviation in the areas of the two polygons, for each of the main component of the flow regime (3 final values).

Extension to European level

The method makes use of physically-based indicators that are applicable in different contexts. Therefore there are no particular limitations in using IAHRIS in other European countries beyond Spain.

Box 4.4: Hydropeaking and thermopeaking

Indicators of hydrological alteration are based, at best, on daily discharges. This prevents the analysis of hydrological alterations that occur at shorter time scales, such as hydropeaking (as well as thermopeaking), that have very important effects on ecological communities as well as channel morphology. The lack of methods for analysing hydropeaking has been identified as one of the main gaps of hydrological assessment methods (Belletti et al., 2015a).

Hydropeaking consists of a repeated sequence of rapid rising and falling discharges artificially caused by flow from powerplants during hydropower production (Gore, 1985; Meile et al., 2011). River hydrology is altered due to unnatural, rapid and significant fluctuations in discharge, which result also in unnatural changes in hydraulic parameters such as water level, flow velocity and bed shear stress. These and the channel morphological changes they induce have effects on almost all living organisms in a river ecosystem, including benthic macroinvertebrates (catastrophic drift) (e.g., Brittain and Saltveit 1989; Cereghino and Lavandier, 1998), fish populations (stranding) (e.g., Cushman 1985; Freeman et al. 2001; Saltveit et al., 2001) and their physical habitat (Valentin et al., 1996), periphyton and mosses (e.g., Brittain and Saltveit 1989). The overall impact generally consists of a decrease in biomass and richness of species, and an alteration in the composition of the macroinvertebrate and fish communities (Meile et al., 2011).

Associated with hydropeaking, **thermopeaking** consists of a sequence of repeated and rapid oscillations in water temperature caused by the release of water from high elevation reservoirs into downstream river reaches (Ward and Stanford, 1979; Toffolon et al., 2010; Zolezzi et al., 2011). In Alpine settings the river water is usually warmed up by the peaking inflow during winter (“warm thermopeaking”) while being cooled in summer (“cold thermo-peaking”) (Zolezzi et al., 2011).

Some EU countries (e.g., Switzerland) have already implemented methods for hydropeaking assessment and mitigation, and other countries (e.g. Austria, Norway) are developing methods with similar objectives.

Recent efforts have been made to assess hydrological alteration by hydropeaking. For example, Meile et al. (2011) proposed the following three indicators to describe the flow regime of rivers in alpine catchments with and without hydropower plants: (1) the seasonal distribution and transfer of water, (2) sub-daily flow fluctuations, and (3) the intensity and frequency of flow changes.

More recently, a **specific method to quantify the level of pressure induced by hydropeaking** on a given river reach has been developed by Carolli et al. (2015). This method is based on two key indicators, modified from the indicators originally proposed by Meile et al. (2011), which measure intensity and rate of variation of hydropeaking, respectively. The method allows classification of the level of pressure by hydropeaking and quantification of the deviation from near natural conditions. Details of this method are provided in **Part 2 Annex A**.

The natural flow regime sustains the ecological integrity of river systems (Poff et al., 1997). The main components of the flow regime (magnitude, frequency, timing, duration, rate of change) influence water, sediment and wood dynamics and thus the hydraulic and physical habitats that are available across flow stages. Therefore, human pressures on hydrological processes undermine the equilibrium of ecosystems. A synthesis of the main relations between natural flow regime components and ecological modification is presented in Table 4.10.

Table 4.10 Ecological responses to alterations of the natural flow regime (based on Walker et al., 1995; Poff et al., 1997, Richter et al., 1998).

Main flow components	Ecological alteration	Ecosystem influences
Magnitude Increased variation	Wash-out; stranding; Loss of sensitive species; Increased algal scour and wash-out of organic matter; Life-cycle disruption;	Habitat availability for aquatic organism; Soil moisture availability for plants; Availability of water for terrestrial animals; Availability of food/cover for fur-bearing mammals; Reliability of water supplies for terrestrial animals; Access by predators to nesting sites; Influences water temperature, oxygen levels, photosynthesis in water column
Frequency Flow stabilization	Altered energy flow; Invasion or establishment of exotic species, leading to: (i) local extinction, (ii) threat to native commercial species, (iii) altered communities; Reduced water and nutrients to floodplain plant species, causing: (i) seedling desiccation, (ii) ineffective seed dispersal, (iii) loss of scoured habitat patches and secondary channels needed for plant establishment; (iv) encroachment of vegetation into channels	Frequency and magnitude of soil moisture stress for plants; Frequency and duration of anaerobic stress for plants; Availability of flood plain habitats for aquatic organisms; Nutrient and organic matter exchanges between river and floodplain; Soil mineral availability; Access for water birds to feeding, resting, reproduction sites; Influences bedload transport, channel sediment textures, and duration of substrate disturbance (high pulses)
Timing / predictability Loss of seasonal flow peaks	Disrupt cues for fish: (i) spawning, (ii) egg hatching, (iii) migration; Loss of fish access to wetlands or backwaters; Modification of aquatic food web structure; Reduction or elimination of riparian plant recruitment; Invasion of exotic riparian species; Reduced plant growth rates	Compatibility with life cycles of organisms; Predictability/avoidability of stress for organisms; Access to special habitats during reproduction or to avoid predation; Spawning cues for migratory fish; Evolution of life history strategies, behavioural mechanisms
Duration Prolonged low flows	Concentration of aquatic organism; Reduction or elimination of plant cover; Diminished plant species diversity; Desertification of riparian species composition; Physiological stress leading to reduced plant growth rate, morphological change, or mortality	Balance of competitive, ruderal and stress tolerant organisms; Creation of sites for plant colonization; Structuring of aquatic ecosystems by abiotic vs. Biotic factors; Structuring of river channel morphology and physical habitat conditions; Soil moisture stress in plants; Dehydratation in animals; Anaerobic stress in plants; Volume of nutrient exchanges between rivers and floodplains; Duration of stressful conditions such as low oxygen and concentrated chemicals in aquatic environments; Distribution of plant communities in lakes, ponds, floodplains; Duration of high flows for waste disposal, aeration of spawning beds in channel sediments
Prolonged baseflow spikes	Downstream loss of floating eggs	
Altered inundation duration	Altered plant cover types	
Prolonged inundation	Change in vegetation functional type; Tree mortality; Loss of riffle habitat for aquatic species	
Rate of Change of hydrologic conditions		
Rapid change in river stage	Wash-out and stranding of aquatic species	Drought stress on plants (falling levels)
Accelerated flow recession	Failure of seeding stablishment	Trapping of organisms on islands, floodplains (rising levels); Desiccation stress on low-mobility stream edge (varial zone) organisms

4.2.3 Morphological assessment

These methods make a geomorphological evaluation of river conditions including assessing channel forms, geomorphic adjustments, or human alterations (Belletti et al., 2015a). They are notably different from a physical habitat assessment, in terms of the incorporated spatio-temporal scales and the approach adopted, including the methods of analysis and the indicators that are defined.

Examples of European morphological assessment methods are SYRAH (Système Relationnel d'Audit de l'Hydromorphologie des Cours d'Eau; Chandesris et al., 2008), MImAS (UKTAG, 2008), IHG (Índice Hidrogeomorfológico; Ollero et al., 2007, 2011), and the Morphological Quality Index (Rinaldi et al., 2013b).

Within REFORM, an extended European version of the Morphological Quality Index (MQI), originally developed in Italy, has been revised and tested.

Morphological Quality Index (MQI)

Reference

Rinaldi et al. (2013b)

See: **D6.2 Part 3: Guidebook for the evaluation of stream morphological conditions by the Morphological Quality Index (MQI)**

Description

The method was designed to comply with the EU Water Framework Directive requirements, but its use can be extended to other applications in river management.

The method is perfectly consistent with the hydromorphological assessment framework developed in REFORM Deliverable D2.1. According to this framework, the spatial scale of application of the MQI is the **reach** (i.e., a relatively homogeneous portion of the river with a length of the order of some km), which is recognised as the most appropriate and meaningful scale for assessing hydromorphology. This substantially differs from the spatial scale of investigation used in physical habitat assessment methods (i.e., the 'site' scale with a fixed length of a few 100 m), which may be not sufficient to fully contextualise current river condition and to perform an accurate diagnosis and interpretation of the causes of any morphological alteration.

The method considers **processes** as well as channel forms. Continuity in sediment and wood flux, bank erosion, lateral channel mobility, and channel adjustments are all included. It includes a temporal component, since an historical analysis of channel adjustments is incorporated, which provides insights into the causes and timing of alterations and into future geomorphic changes.

Reference conditions for the MQI are river reaches in dynamic equilibrium, where the river is performing those morphological functions that are expected for a specific morphological typology, and where artificial elements and pressures are absent or do not significantly affect the river dynamics at the catchment and reach scale.

The method integrates **remote sensing – GIS** analysis and **field survey**. The list of indicators used for the MQI is coherent with the indicators defined in the REFORM assessment framework reported in Deliverable 2.1. It includes a set **twenty-eight indicators** that assess longitudinal and lateral continuity, channel pattern, cross section configuration, bed structure and substrate, and vegetation in the riparian corridor. These characteristics are evaluated by in terms of the following three components.

(1) **Geomorphological functionality** evaluates 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.

(2) **Artificiality** assesses the presence and frequency of artificiality (artificial elements, pressures, interventions, management activities) independently of the effects of these

artificial elements on processes.
(3) **Channel adjustments** assess relatively recent morphological changes (i.e., about the last 100 years) that are indicative of a systematic instability related to human factors.

Three classes are defined for most indicators (a few exceptions have two or more than three classes): (A) undisturbed conditions or negligible alterations (reference conditions); (B) intermediate alterations; (C) very altered conditions. The evaluation is based on a scoring system, assuming that reference conditions can be identified within a river reach that is in dynamic equilibrium, is performing those morphological functions that are expected for a specific morphological type, and where artificial elements and pressures are absent or are not significantly affecting river dynamics. Scores have been defined by the Authors of the original method (Rinaldi et al., 2013b) and they remain unchanged in this extended version, in order to ensure data comparability when applied to different European countries. A total score is computed as the sum of scores across all components and aspects, and the final result is the Morphological Quality Index (MQI), which ranges from 0 (minimum quality) to 1 (maximum quality).

Extension to European Level

The MQI has been originally developed for application in Italy, i.e., covering the full range of physical conditions, morphological types, degree of artificial alterations, and amount of channel adjustments. The original version has been tested (Rinaldi et al., 2013b), and then applied to a large number of river reaches in Italy, since the index has been approved as standard hydromorphological assessment method for the WFD classification and monitoring, and therefore has been used in the first cycle of RBMPs.
During the REFORM project, the method has been extended and tested on a number of European streams (Nardi et al., 2015), including lowland rivers with very low energy and an anabranching (anastomosing) morphology, which were under-represented in the original version. Therefore, during the REFORM project, an effort has been made to better cover such situations as well as some specific alterations which are more common in other countries. Therefore, the structure and list of indicators has remained the same as the original MQI, but with some additional consideration of aspects which were not completely covered before.

Three examples of other morphological assessment methods developed in Europe are described below.

Morphological Impact Assessment System (Rivers-MImAS)

Reference

UKTAG (2008)

Description

MImAS is the method used for WFD classification in Scotland and was developed by the Scottish Environmental Protection Agency (SEPA). It is a morphological impact assessment system and decision support tool which identifies whether morphological alterations/changes (interventions) may cause risk of failure in achieving ecological objectives (related to WFD).
It is mainly based on desk study of existing data (maps and aerial photos) to identify impacts (Morphology Pressures Database), structure and extent of riparian vegetation cover (Riparian Vegetation Database). Field survey collects additional data where necessary (mainly on pressures).
The impact on morphological conditions (system capacity) is assessed through 5 semi-independent modules: (1) the attribute module (for morphological and ecological function and condition); (2) the typology module (to select attributes proper for each river type); (3) the sensitivity module (ecological and morphological sensitivity assessment: resistance and resilience); (4) the pressure module (25 pressures); (5) the scoring system (a numerical 'impact rating' by combining the results from previous modules). The '% capacity used' for the section of river considered is calculated by

combining the 'impact rating' of the alteration of a given river length (type of alteration and affected river length). These are then added for all morphological alterations.

Extendibility at European level

The method has been implemented for the WFD in Scotland and used during the first cycle of RBMPs. *MiMAS* has been developed with a specific consideration of river morphologies in the Scottish context. A wider application across Europe is feasible but needs to be tested.

Système Relationnel d'Audit de l'Hydromorphologie des Cours d'Eau (SYRAH)

Reference

Chandesris et al. (2008, 2009)

Description

The method provides an audit system for making an inventory and analysing hydromorphological alterations (impacts) on water courses at catchment scale, but also their effects at finer scales. It has been developed to comply with the Water Framework Directive requirements.

The method is based on the compilation of existing data (e.g. land cover, cartographic, geological, soil erosion maps, etc.) and the use of GIS techniques. Starting from the census of human artificial features (i.e. impacts), an environmental risk assessment logic (DPSIR) can be applied to define the risk of hydromorphological alteration (i.e. the product between stressor spatial extent and its effect on ecosystems). The risk assessment considers alteration of flow (3-5 parameters), sediment flux (3 parameters) and morphology (6 parameters).

The result of the risk assessment can be shown through risk maps based on the location and intensity (extent) of artificial structures and the severity of their effect on ecosystems.

Extendibility at European level

The method has been implemented for the WFD in France and used during the first cycle of RBMPs. The method allows spatial comparison at the national scale. It is an open system that could be adapted for application to other European contexts.

Index for hydromorphological quality assessment of rivers and streams (IHG)

Reference

Ollero et al. (2007, 2008, 2011)

Description

The method provides a procedure for the analysis of the hydromophological status of rivers and streams. The method considers the main sources of alteration of the natural or reference hydromorphological condition of the river. Taking into account the structure of the method, it may be applied for assessing the present hydromorphological condition, or for simulating different hydromorphological scenarios associated to various types and degrees of river management/restoration.

The method allows the assessment of hydromorphological quality by scoring: 1) the functional quality of the fluvial system, including a) flow regime naturalness, b) sediment supply and mobility, and c) floodplain functionality; 2) the channel quality, including a) channel morphology and planform naturalness, b) riverbed continuity and naturalness of the longitudinal and vertical processes, and c) riverbank naturalness and lateral mobility; and 3) the riparian corridor quality, including a) longitudinal continuity, b) riparian corridor width, and c) structure, naturalness and cross-sectional connectivity.

Each parameter has an initial score of 10, corresponding to the natural state and functionality of the system. However, after the impacts and pressures are assessed, points are deducted from this initial value according to different criteria. The full IHG hydrogeomorphological assessment of each river reach is performed by adding the nine values obtained, with a highest possible score of 90 points.

Extendibility at European level

The procedures has been developed for the WFD in Spain, and used in a wide range of assessments of the status of Spanish rivers, and in a number or restoration initiatives. Lastly, the main components of the method have been included in the Spanish Protocol for the hydromorphological characterization of rivers (Aparicio et al., 2015). Its structure allows its application and adaptation to other European countries and regions.

Alterations of connectivity from sediment sources and/or disruption of sediment continuity in the fluvial network may be a major cause of alteration of morphological conditions. To account for the sediment regime as a fundamental basis for sustainable morphodynamics, a specific assessment method has been developed in the context of REFORM named **Hydromorphological Evaluation Tool** (**HYMET**) (Habersack and Klösch, in prep.). In a hierarchical manner, HYMET considers sediment supply from the catchment, and sediment transfer to the evaluated reach. At the reach scale, the artificiality and the sediment budget are assessed. No reference condition is needed for determining hydromorphological alterations. Here, with (partially) re-established sediment supply and reduced artificiality, a river reach is expected to develop the morphodynamics that approaches an undisturbed condition. This assessment can be used to integrate the previous methods. A detailed description of the method, together with an application to an Alpine case study, are reported in **Part 5** (Applications) of this Deliverable.

4.2.4 Assessment of riparian vegetation

A full hydromorphological assessment of a river and its floodplain must incorporate an assessment of the riparian vegetation. Therefore, this type of assessment concerns the vegetation of the riparian corridor, with a particular emphasis on the functional aspects related to geomorphological processes.

Several methods for assessment of riparian vegetation have been developed within Europe (see reviews by Fernández et al., 2011; Belletti et al., 2015). Some aspects of vegetation related to the functioning of geomorphic processes are also investigated in some morphological assessment methods (e.g., the MQI includes indicators of riparian vegetation), but there are other essential riparian features which should be additionally assessed (such as the percentage of non-native species; vegetation age classes or pioneer species recruitment, indicative of riparian corridor dynamics González del Tánago et al., 2015; and specific vegetated pioneer landforms indicative of vegetation-hydromorphology interactions, (Gurnell et al., 2014)). This can be achieved by integrating the morphological assessment with the application of a specific method of riparian vegetation assessment. In this report, one of these methods has been selected for application within REFORM because it is consistent with the overall hydromorphological framework (in terms of spatial scales, indicators, and survey methods). This method is briefly described below.

Riparian Quality Index (RQI)

References
González Del Tánago and García De Jalón (2011)

Description
The method provides a useful tool for **monitoring and evaluating the structure of riparian zones**, as an element of the river morphological conditions, and to comply with the Water Framework Directive requirements.
It has been designed to be applied at the **'reach' scale**, i.e. a river portion with relatively homogeneous riparian structure in terms of boundary conditions (landscape, valley and river type, hydrological conditions, floodplain characteristics).
The method assesses several **vegetation features** (e.g. longitudinal and lateral connectivity, plant regeneration, structure and composition, soil, etc.) without being a time-consuming floristic survey. It also incorporates some **hydromorphological** (e.g. bank dynamics, flow and flood regime) **and vegetation processes** (e.g. age diversity and plant regeneration).
The survey is carried out mainly in the **field**, but the Authors also recommend an analysis of recent **remote sensing** sources prior to field work.
The evaluation procedure incorporates **7 main indicators** (Table 4.11), 3 of which are applied twice (i.e. to both river margins). Each indicator is evaluated on the basis of a 15 points score system grouped into 5 quality classes (i.e. each of the 5 classes is composed by 3 different scores of quality). A total score is computed as the sum of scores across all indicators, which corresponds to the *RQI* (Riparian Quality Index), ranging from 130-150 (best status) to less than 10 (worst or very bad conditions).

Table 4.11 Indicators used in the Riparian Quality Index (RQI) (from González Del Tánago and García De Jalón, 2011).

Indicators and description
1. Dimensions of land with riparian vegetation Identify the band containing riparian species and estimate its average width along the study reach. Look for restrictions to riparian corridor width due to human influences. If they do not exist, any width would be considered very good status. Take into account that riparian dimensions can be naturally reduced in confined valleys due soil constraints or the presence of adjacent slopes.
2. Longitudinal continuity, coverage and distribution pattern of riparian corridor (woody vegetation) Estimate longitudinal continuity and coverage based on the distribution pattern of woody vegetation associations. Estimate intensity of fragmentation based on size and frequency of open areas created by

human actions, and land-use within these areas compromising corridor functions.

3. Composition and structure of riparian vegetation

Identify natural composition and strata structure of riparian vegetation and natural succession stages for the study reach. Look for differences between this potential vegetation and actual vegetation forms, number and coverage of exotic species and abundance of mats, reeds, nitrophilous or ruderal species.

4. Age diversity and natural regeneration of woody species

Look for age diversity of main woody species. Try to locate where regeneration takes place and search for the main causes limiting regeneration when they exist.

5. Bank conditions

Look for indicators of naturalness (mobility, bank- attached land forms, presence of woody debris and vegetation detritus, heterogeneity of water shoreline, etc.). Search for human influence determining bank instability, homogeneity of the water shoreline, vegetation overgrowth of banks, incision or fine sediment deposition, revetments or direct alterations of bank-form, bank-height and bank-slope.

6. Floods and lateral connectivity

Look for intensity of flow regulation altering frequency and magnitude of floods and periodicity and area of flooding; and identify morphological changes or channelization works for preventing overflowing onto the floodplain. In the absence of flow data, look for inundation footprints on riparian and floodplain areas, such as woody debris and waste hanging on vegetation after floods, open gravel and sand areas associated with secondary flood channels, vegetation detritus location, etc. Or assess lateral connectivity based on proximity of visible physical restrictions of flow accessibility into the riparian zone.

7. Substratum and vertical connectivity

Look for alterations of the soil surface reducing natural infiltration capacity; and for alterations of substratum within soil profiles that reduce the original alluvial permeability, subsurface flows and groundwater connectivity. Alterations can be due to infillings that modify the original soil material and seed-bank and reduce the composition and diversity of native herbaceous communities: or to gravel mining that induces particle size changes or replaces the original materials; or due to the presence of underground infrastructure that prevents subsurface flows.

Extendibility at European level

The method has been designed and tested on a large range of Spanish river types; for its application to other European contexts it would need some validation.

4.2.5 Survey and classification of geomorphic units

The spatial scales of geomorphic and smaller (hydraulic, river element) units are the most appropriate to assess the presence and diversity of **physical habitats**. Geomorphic and hydraulic units are generally associated with the mesohabitat or biotope scale, while river elements coincide with the microhabitat scale. Geomorphic units (e.g., riffles, pools, etc.) constitute distinct habitats for aquatic fauna and flora, and may provide temporary habitats (refugia from disturbance or predation, spawning, etc.).

A **geomorphic unit** is defined as an area containing a landform created by erosion and/or deposition inside (instream geomorphic unit) or outside (floodplain geomorphic unit) the river channel. Geomorphic units can be sedimentary units, or can include living or dead (e.g. large wood) vegetation ('biogeomorphic units'). A single geomorphic unit can include from one to several **hydraulic units**, i.e. spatially distinct patches of relatively homogeneous surface flow and substrate character, each of which can include a series of **river elements**, i.e. individuals and patches of sediment particles, plants, wood pieces, etc.

As originally recognised by Frissell et al. (1986), procedures to **assess physical habitat** need to be ecologically and geomorphologically meaningful, so that ecologically relevant scales and physical variables are incorporated into a geomorphological characterization. Because geomorphic units constitute the physical basis for habitat units, an assessment of the assemblage of geomorphic units provides information about the range of habitats occurring in a given a reach.

Geomorphic units are linked to the **reach scale**, given that processes of water flow and sediment transport that control the geomorphic units are influenced by factors acting at the reach (e.g., slope, substrate, and valley configuration) and larger scales. Reaches of the same morphological type usually exhibit similar assemblages of geomorphic units. As a consequence, physical habitat characteristics and associated biotic conditions are strongly influenced by reach scale physical factors, which in turn are constrained by regional-, catchment-, and segment scale considerations.

A new **system for the survey and classification of geomorphic units** (GUS) in streams and rivers has been developed in the context of REFORM. The system can be integrated with the Morphological Quality Index (MQI) and allows the establishment of links between hydromorphological conditions at reach scale, characteristic geomorphic units, and related biological conditions.

Geomorphic Units survey and classification System (GUS)

References

Belletti et al. (2015c)

See: **D6.2 Part 4: The Geomorphic Units survey and classification System (GUS)**

Description

The GUS is an open-ended, flexible framework for the survey and classification of geomorphic units.

Geomorphic units are organized within a nested hierarchical framework as follows:

- **Macro-unit**: this is an assemblage of units of the same type, e.g. aquatic portions, sediment, vegetation.
- **Unit**: this is the basic spatial unit, and corresponds to a feature with distinctive morphological characteristics and significant size, e.g. riffle, bar, island.
- **Sub-unit**: this corresponds to patches of relatively homogeneous characteristics in terms of vegetation, sediment and/or flow conditions.

Survey of geomorphic units can be carried out at different levels of characterization with increasing details defined as follows:

- **Broad level**: a general characterization of macro-units, i.e. presence/absence, areal extension and/or percentage relative to the spatial settings. It is carried out exclusively by remote sensing and GIS analysis, and can be applied to rivers of sufficient size in relation to image resolution.

- **Basic level**: a complete delineation and first level of characterization of all geomorphic units, i.e. presence/absence, number, area/length. Some macro-unit types can also be described at this level. It is mainly carried out by field survey, but remote sensing and GIS analysis are also used, particularly for large rivers or where very high spatial resolution imagery is available.
- **Detailed level**: aims to (i) provide more detailed information and data for units (and some macro-units) on genetic processes, morphological, hydrological, vegetation and sediment properties; (ii) describe macro-units and unit sub-types (when applicable); (iii) characterise sub-units.

Based on the geomorphic units survey, two synthetic **GUS indices** (**GUSI**) are defined: (1) a geomorphic units *Richness index* (GUSI-R); (2) a geomorphic units *Density Index* (GUSI-D). These indices can be used to better characterise the assemblage of geomorphic units, and to monitor the trend of changes in geomorphic units in a given reach (decrease or increase in richness and density) as a consequence of possible pressures or interventions. The results of the GUS (including the indices) at the site-scale must be necessarily combined with a MQI assessment at reach-scale to better interpret the significance of a diversity (richness and density) of geomorphic units and its relevance.

Extendibility at European level

The GUS has been developed to be applied at European level, so it comprises the entire range of possible geomorphic units in different European contexts.

The classification and characterization of geomorphic units can support increasing levels of knowledge concerning the landscape character and behaviour of a river system through the consideration of the following aspects (Brierley et al., 2013):
(1) Identify and interpret geomorphic units and their process-form relationships;
(2) Analyse the assemblage of geomorphic units at the reach scale and interpret how they adjust over time (i.e. the behavioural regime of the river);
(3) Explain controls on the assemblage of geomorphic units at the reach scale and how they adjust over time;
(4) Integrate understanding of geomorphic relationships at the catchment scale.

Main Outputs of Stage II - Step 2

- GIS mapping synthesizing pressures and critical reaches at catchment scale
- Summary Tables and/or GIS mapping of the hydrological state of the investigated rivers
- Summary Tables and/or GIS mapping of the morphological state of the investigated rivers
- Summary Tables and/or GIS mapping of the riparian vegetation state of the investigated rivers
- Summary Tables and/or GIS mapping of the geomorphic units existing along the investigated reaches
- Based on the previous outputs, identification of the problems and the most critical reaches at catchment scale, where some improvement of hydromorphological conditions may be needed

Habitat modelling

Altering river flow regime acts on biota through a hydraulic template, which is mediated by channel morphology (Dunbar et al., 2012). Therefore, modelling river hydro-morphological characteristics (i.e., the physical habitat) has been widely used for viewing the ecological impacts of flow regulation (Maddock et al., 2013).

The underlying premise of all habitat modelling tools is that biotic communities in rivers are limited by habitat events. Thus, river restoration objectives can be defined to meet specific habitat requirements of both aquatic and riparian species. Modelling the spatio-temporal variation of physical habitat characteristics, such as water depth, flow velocity, substrate composition, channel geometry and cover availability, is then used to predict species' distribution and abundances, assess environmental flows and design river restoration measures (Merritt et al., 2010, Parasiewicz et al., 2012, Heggenes and Wollebaek, 2013).

Traditional habitat models (e.g., PHABSIM, Bovee et al., 1998) works at the microhabitat scale, referring to a single point (or river element) which is evaluated in terms of habitat suitability due to its local hydraulic conditions. Originally, these tools were based on data from river cross-sections and one-dimensional hydraulic model (with simple unit-roughness methods) to translate discharge (or flow in units of volume/time) into patterns of water depth and flow velocity. Since the end of the 1990s, multidimensional hydraulic models (two- or three-dimensional; Crowder and Displas, 2002; Shen and Diplas, 2008) have been used to describe detailed channel hydraulics to open up access to additional hydraulic descriptor variables, such as shear stresses, turbulence and secondary velocities, and improved capability to study direct interactions between hydraulic variables and species distribution. However, such hydraulic models are suited for larger gravel-bedded rivers and are more challenging to apply in high-energy systems with exposed cobbles and boulders (Vezza et al., 2014), in lowland macrophyte-dominated rivers (Hearne et al., 1994) and in rivers with winter ice (Alfredsen and Tesaker, 2002).

Although hydraulic variables are important in habitat assessment, other factors such as cover availability (e.g., presence of boulders, undercut banks, overhanging vegetation), water temperature, shore characteristics, and biotic interactions may be of greater importance in limiting species biomass or abundance (Gordon et al., 2004). These environmental conditions around an organism, not at the point where it is observed, are known to be important factors affecting habitat use.

In order to cope with this issue, the use of the mesohabitat scale and multivariate habitat suitability models has recently increased (e.g., MesoHABSIM, Parasiewicz et al., 2013). In particular, machine learning techniques currently represent an appropriate method to analyze the relationship between species distribution and several explanatory environmental factors collected at the mesohabitat scale (e.g., Vezza et al., 2015; Wilkes et al., 2015).

Across different disciplines (including aquatic ecology, eco-hydraulics and geomorphology) mesohabitats correspond in size and location to geomorphic or hydraulic units. Therefore, the integration of meso-scale habitat models with the Geomorphic Units survey and classification System (GUS) can define a more consistent modelling framework, which can offer some advantages over the current methodology of physical habitat assessments. For instance, meso-scale habitat models integrated with GUS (i) can allow data to be collected at a more appropriate scale for addressing environmental river management problems; (ii) may limit questions about the degree to which any particular reach (or cross-section) represents a longer stretch of river of management interest; and (iii) the method allows results to be upscaled to river sectors or entire catchments, which are spatial scales more relevant to the life-history strategies of many aquatic and riparian species.

In Rinaldi et al. (2015b), the GUS is used to integrate the mesohabitat simulation model MesoHABSIM and to assess spatio-temporal alterations of habitat structure in Italian rivers. In addition, two new habitat indices, based on GUS and MesoHABSIM, were developed and applied to assess the habitat integrity for fish in different river environments. Firstly, the **Index of Spatial Habitat availability (ISH)** is used to describe the average amount of habitat loss due to a particular pressure, secondly, the **Index of Temporal Habitat availability (ITH)** is used to measure the increase of continuous duration of events when habitat bottlenecks create stress to the fauna.

The two habitat indices, ISH and ITH, are calculated as follows:

- Based on GUS, geormorfic units are delineated and classified at different flow conditions. Detailed hydromorphological surveys can be repeated from three to five times depending on the hydrological regime of the river and the objectives of the study (Figure 4.11).
- Through the MesoHABSIM model, the habitat-flow rating curve and the habitat time series are generated for each target species (and life stages) in the period of interest.
- Using habitat time series, the ISH is calculated for each fish species (and life stages) as the ratio between the average available area (expressed in m^2) in reference ($A_{Hd,r}$) and altered conditions (A_{Hd}). The ISH value for the entire fish community is then defined by the minimum value among all target species (and life stages) in the river section (Eq. 1).

$$\mathrm{ISH} = \min\left(\begin{cases} 1-\frac{|A_{Hd,r}-A_{Hd}|}{A_{Hd,r}}, & \frac{|A_{Hd,r}-A_{Hd}|}{A_{Hd,r}} \le 1 \\ 0, & \frac{|A_{Hd,r}-A_{Hd}|}{A_{Hd,r}} > 1 \end{cases}\right)_{\mathrm{species}} \qquad \text{Eq.1}$$

- To calculate the ITH, habitat time series are statistically analyzed using the Uniform Continuous Under Threshold (UCUT) curves (Parasiewicz et al., 2013). Specifically, the ITH compares duration and frequency of under-threshold events in both reference and altered conditions using Q_{97}, (i.e., the flow value exceed 97% of the time) as reference habitat threshold (A_{Q97}, *sensu,* Parasiewicz et al., 2012). An indicator of Stress Days Alteration (SDA) reports the average distance between two UCUT curves representing cumulative duration of habitat under-threshold events in reference (dc,r,AQ97) and altered (dc,AQ97) conditions (Eq.2). The index ITH for each species (and life stages) is finally calculated using a negative exponential curve (Eq. 3) and the ITH community value is given by the minimum value among all target species.

$$\mathrm{SDA} = \frac{1}{\mathrm{d}_{\max,r}} \cdot \sum_{k=1}^{k=\mathrm{d}_{\max,r}} \left(\frac{\left| \mathrm{d}_{c,AQ97} - \mathrm{d}_{c,r,AQ97} \right|}{\mathrm{d}_{c,r,AQ97}} \right) \qquad \text{Eq. 2}$$

$$\mathrm{ITH} = \min\left(e^{-0.38\,\mathrm{SDA}}\right)_{\mathrm{species}} \qquad \text{Eq. 3}$$

Depending on the study objectives, indices' calculation can be performed at both intra- and inter-annual scale, and using both daily and hourly discharge (e.g., Figure 4.12). Hourly streamflow records are considered suitable for rivers affected by hydropeaking, due to the particular time-scale of hydropower production and dam operations. Moreover, in areas where specific conservation objectives are required, index values can be calculated for single taxa, allowing restoration strategies to be focused on especially threatened species.

Results derived from habitat indices applications showed the potential of linking GUS to habitat modelling and evaluation, in order to provide useful indicators that can be used for both hydro-morphological and ecological status assessment.

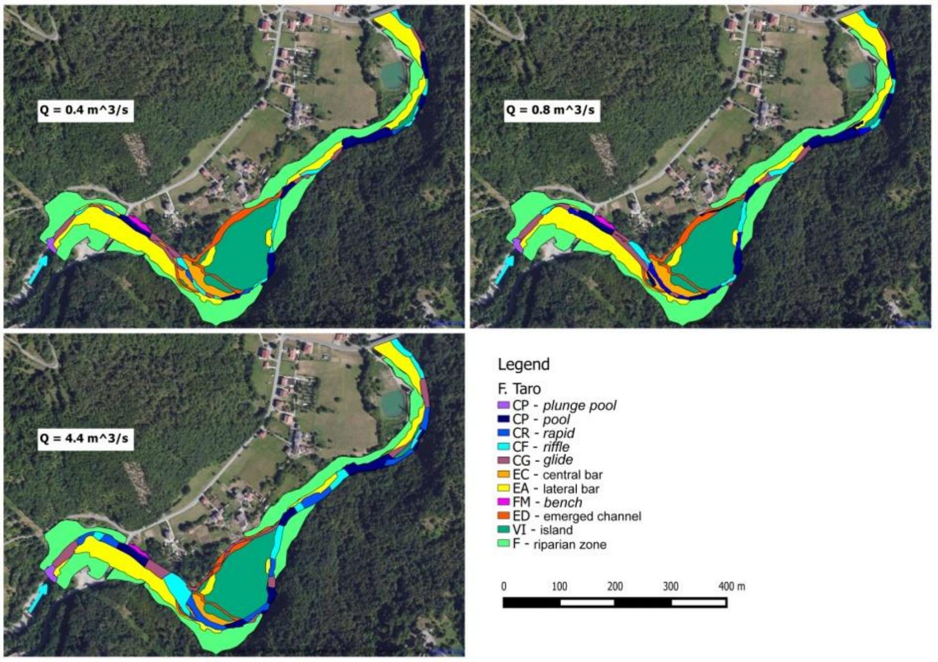


Figure 4.11 Spatial distribution of channel and floodplain geomorphic units for the Taro River (Parma, Italy) for three different flow conditions (0.4 m^3/s, 0.8 m^3/s, 4.4 m^3/s).

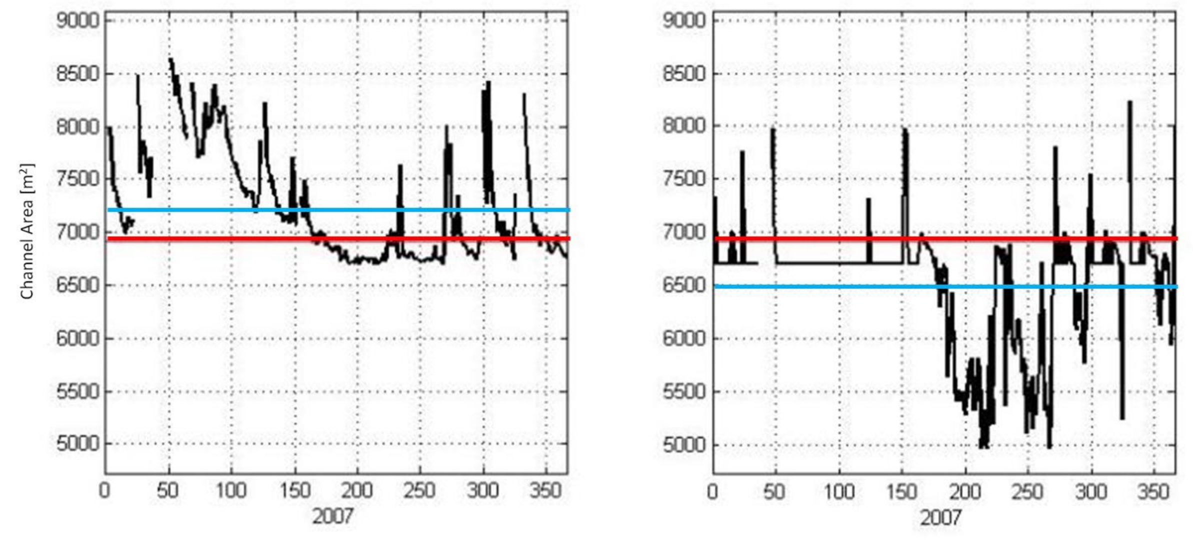


Figure 4.12 Habitat time series for reference (left hand side) and altered (right hand side) conditions for barbel (*Barbus* sp.) in the Taro River (Parma, Italy) in 2007. Blue solid lines represent average values of habitat availability used to calculate the ISH. Red solid lines refer to the minimum habitat threshold during low flows (A_{Q97}) in reference conditions, which is used to generate UCUT curves and calculate the ITH value.

4.3 Step 3: Monitor hydromorphological conditions

After assessing reach conditions, a following step is to monitor those conditions, i.e. to carry out periodic measurement of parameters or indicators to assess whether changes are occurring relative to an initial condition.

Monitoring can be used: (1) in the context of the WFD (surveillance, operational, investigative); (2) to evaluate the effects of management or restoration interventions. There are obvious interactions with stage III (assessment of scenario-based future trends), and stage IV (design of management or restoration actions). For example, monitoring the state of a water body can determine a management decision (‘adaptive’ management), such as the choice of some action (for example if the monitoring results show that the conditions are deteriorating) or of preservation of existing conditions. On the other hand, monitoring can follow the phase of design and implementation of a restoration project (post-project monitoring) or another type of intervention.

Basic Questions of Stage II - Step 3

- Have some *changes in hydromorphological conditions* occurred compared to an initial state and/or to a previous assessment?
- What is the *temporal trend* and the spatio-temporal pattern of changing parameters or indicators?
- What are possible *causes* of changes in hydromorphological conditions?

A list of **indicators for hydromorphological monitoring** is reported in Table 4.12. The table includes (first column) the main components of a hydromorphological assessment according to the WFD (continuity, morphology, substrate) to make a more direct link with WFD requirements. A detailed description of hydrological, morphological and vegetation assessment indicators and monitoring protocols is reported in **Part 2** of this deliverable. This includes, for each indicator, detailed information on monitoring methods (e.g., field survey, remote sensing), measurement procedure (e.g., definition of transects, etc.), ranges of application, spatial scale, and frequency of measurement.

The criteria for selecting reaches and indicators to be monitored depend on the aim of the monitoring. The list of indicators in Table 4.12 and in the Annexes represents a list of potential indicators that could be used, but a selected number of indicators is often needed for monitoring specific aspects.

Note that **ecological indicators** are not included in this Deliverable, as they are described in other parts of REFORM (see the box on Links at the end of Stage II).

Table 4.12 Summary of indicators for monitoring hydromorphological conditions.

Components	Key processes	Hydrology	Morphology	Vegetation	Artificiality
Longitudinal continuity	Water flow	IHA, hydropeaking, channel-forming discharge			Alteration of water flow (dams, impoundments, water abstraction, hydropower)
	Sediment flow		Suspended sediment load Bedload		Alteration of sediment flow (dams, check dams, weirs, bridges)
	Vegetation succession			Longitudinal continuity of riparian corridor structure	Riparian corridor fragmentation (vegetation cutting)
				Spatial heterogeneity (number of different land cover units per corridor length)	
	Wood delivery				Alteration of wood delivery from upstream and wood transport (dams, check dams, bridges)
Lateral continuity	Water flow	Groundwater			Groundwater abstraction
	Flooding		Presence and extension of modern floodplain		Bank protections, artificial levees
	Sediment supplied from hillslopes to the channel				Elements of disconnection (roads, landslide protection) on hillslopes adjacent to the channel
	Bank processes		Bank sediment size (D_{50})		Proportion of protected banks
			Eroding banks		
			Laterally aggrading banks		
			Lateral channel migration rate		
			Width of erodible corridor		

Table 4.12 (continued).

Components	Key processes	Morphology	Vegetation	Artificiality
Lateral continuity	Vegetation succession		Patterns of transversal distribution of floodplain / riparian vegetation	Alteration of lateral vegetation structure / encroachment (vegetation cutting)
			Floodplain / riparian vegetation connectivity	Groundwater abstraction
Pattern	Self-maintenance / channel adjustments	Bankfull sinuosity index, Braiding index, Anabranching index, River type		Artificial changes of river course (meander cutting, channelization, etc.), bank protections, dams, check dams, weirs
	Vegetation succession	Presence, variability and extent of instream geomorphic units		
		Presence of aquatic plant-dependent geomorphic features		
		Presence, variability and extent of geomorphic features in the alluvial plain (including wood)		
			Emergent aquatic plant extent, patchiness, species	Vegetation management (selective cutting, total removal)
			Riparian corridor width	
			Riparian corridor coverage	
			Riparian vegetation patchiness, species	
			Age diversity of pioneer and late – seral species	
			Extent of riparian recruitment sites (bare gravel bars and bare soil)	
				Floodplain occupation
				Number and coverage of invasive species

Table 4.12 (continued).

Components	Key processes	Morphology	Vegetation	Artificiality
Longitudinal profile/Cross-section	Self-maintenance / channel adjustments	Specific stream power (at current mean bankfull width and morphologically meaningful discharge)		
		Bed elevation		Structures altering longitudinal profile and/or cross section (check dams, bank protections, etc.)
		Bed slope		Interventions altering longitudinal profile and/or cross section (sediment removal)
		Bankfull channel width		
		Bankfull channel depth		
		Width : depth ratio		
		Variability of cross section		
Bed substrate (including vertical connectivity)	Self-maintenance / channel adjustments	Bed sediment size (D_{50})		Structures or interventions altering bed substrate (revetments, ramps, sills, sediment removal)
		Bed armouring		
		Clogging		
		Bedrock outcropping		
			Presence of in-channel large wood	Wood removal

Monitoring results can be used to: (1) verify whether a reach or an entire water body is changing its condition; (2) evaluate the effects of restoration or management interventions. Two main approaches can be used for these aims as follows (see also **Part 2 - Thematic Annex B**).

(1) Monitoring and analysis of temporal trends of hydromorphological indicators
This approach consists of conducting periodic measurements of some selected morphological parameters or indicators, which can be used to visualise and analyse temporal trends. This type of approach is particularly suitable for a detailed investigation and comprehension of specific aspects of river adjustment and relative causes. Selection of monitoring parameters depends on the characteristics of each case, including: (1) the objectives of the monitoring; (2) the hydromorphological characteristics of the investigated reach; (3) the type of pressure, i.e. the parameters more sensitive to the investigated pressure must be selected.
For a given morphological parameter (e.g., bed elevation, bankfull channel width, etc.), two types of representation can be generally used: (1) *spatio-temporal distribution* by plotting the parameter versus distance downstream (at reach scale) for different years (Fig. 4.11A); and (2) *temporal trend*, by plotting the parameter "at-a-station" (i.e., in a specific cross-section) or the reach-averaged value of the parameter versus time (Fig. 4.11B).

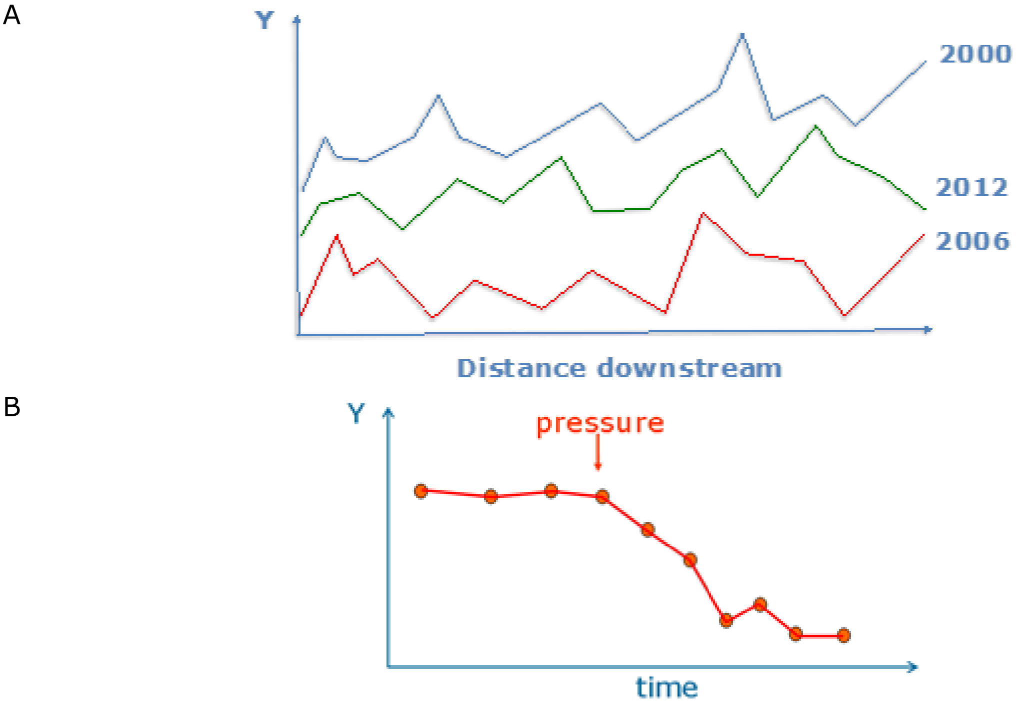


Figure 4.11 Representation and visualization of temporal changes of a morphological parameter. A) Spatio-temporal distribution; B) Temporal trend.

(2) Periodic evaluation by assessment methods
Periodic application of a hydromorphological assessment method provides a synthetic index of current conditions, e.g. one of those described in step 2. In this way, it is possible to assess the tendency of this index to change in response to some variation induced by an intervention or restoration measures, or in response to the trajectory of channel changes occurring independently in response to new interventions.

For these aims, the Morphological Quality Index for monitoring (**MQIm**) is a particularly suitable tool. The MQIm is an extension of the MQI that is used for the specific aim of monitoring morphological conditions in the short term, i.e. to evaluate the tendency of morphological conditions (enhancement or deterioration) (see **Part 3** for details).

Main Outputs of Stage II - Step 3

- Summary Tables or reports on monitored parameters or indicators, and on changes of hydrological, morphological or riparian vegetation indices
- Graphs showing the spatio-temporal distribution and temporal trend of specific, changing parameters or indicators

Links

- The Morphological Quality Index (MQI) is reported in detail in the **Part 3: Guidebook for the evaluation of stream morphological conditions by the Morphological Quality Index (MQI)**
- The Geomorphic Units survey and classification system (GUS) is reported in detail in the **Part 4**.
- Protocols of the monitoring indicators are reported in the **Thematic Annexes of Part 2**.
- **Ecological monitoring indicators** are not included in this deliverable, as they are widely discussed in other Work Packages (e.g., WP3) and summarised in the **Wiki** and in the REFORM **Deliverable 6.3**.

5. Stage III: Assessment of scenario-based future trends

In order to identify possible restoration actions and select the reaches in the fluvial system where these actions are most likely to be successful, some prediction of the potential morphological changes that could occur in a given reach or segment is fundamental. Evaluation of the reaches with a higher potential for morphological changes provides a helpful first screening of the portions of the catchment where morphological improvement is most likely to be feasible and supports the setting of priorities in terms of restoration strategies (e.g., natural morphological changes vs. morphological reconstruction).

Possible restoration actions and strategies must be placed in the context of potential future trends of river conditions. Based on the knowledge of past evolutionary trajectories, it is important to evaluate the potential morphological changes that could occur under different scenarios in order to select management actions which would be compatible with these changes and would maximize human benefits related to the most likely future river conditions.

Therefore, this Stage represents the interconnection between the diagnostic phase (Stage II) and the phase of identification of possible restoration actions (Stage IV).

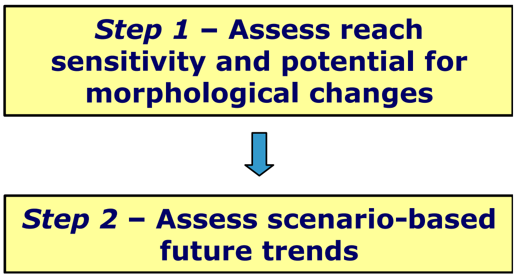


Figure 5.1 Steps of Stage III.

5.1 Step 1: Assess reach sensitivity and potential for morphological changes

In order to select appropriate and sustainable actions (Stage IV), it is crucial to evaluate the likelihood that morphological changes enhancing functionality and geomorphic conditions will take place in an expected time scale, and that these modifications will be sustainable.

Basic Questions of Stage III - Step 1

- What is the *sensitivity* of the investigated river reaches? Are the river type, past morphological changes and/or current trends of adjustments indicative of a sensitive reach?
- Do the *evolutionary trajectories* indicate that past changes are continuing with the same trend, or that the trend has stabilised or reversed, or that some threshold has been exceeded?
- What is the *connectivity* of the investigated reaches with upstream and downstream portions of the catchment?

- What is the *potential* for improvement of morphological conditions of the investigated reaches?

Sensitivity is a fundamental indicator for selecting interventions aimed at improving geomorphic conditions. Two basic strategies can be potentially adopted to achieve an improvement of geomorphic conditions: (1) natural morphological change or self-adjustment can be supported; (2) morphological reconstruction can be implemented. The scheme in Figure 5.2 shows a hypothetical trend of sensitivity and emphasises that the choice of the type of intervention (morphological change vs. reconstruction) will depend on the sensitivity of the reach.

Supporting **morphological change** is the most sustainable approach since it is based on the reactivation of processes (i.e. a *'process-based'* strategy), but the river must have sufficient energy for the natural processes of erosion and sedimentation to occur and lead to dynamic morphological changes in an acceptable time scale. In contrast, **morphological reconstruction** involves the re-creation of erosional or depositional forms (such as bars, meanders, etc.) with no attempt to reactivate the processes which are responsible for such forms (i.e. a *'form-based'* strategy). This latter type of strategy should be limited to situations where energy is low and the river has low sensitivity (or reactivity) and, therefore, a limited potential for natural morphological improvement. In such a case, natural 'recovery' could only occur over a very long period, and so actions are necessary to directly shape channel morphology.

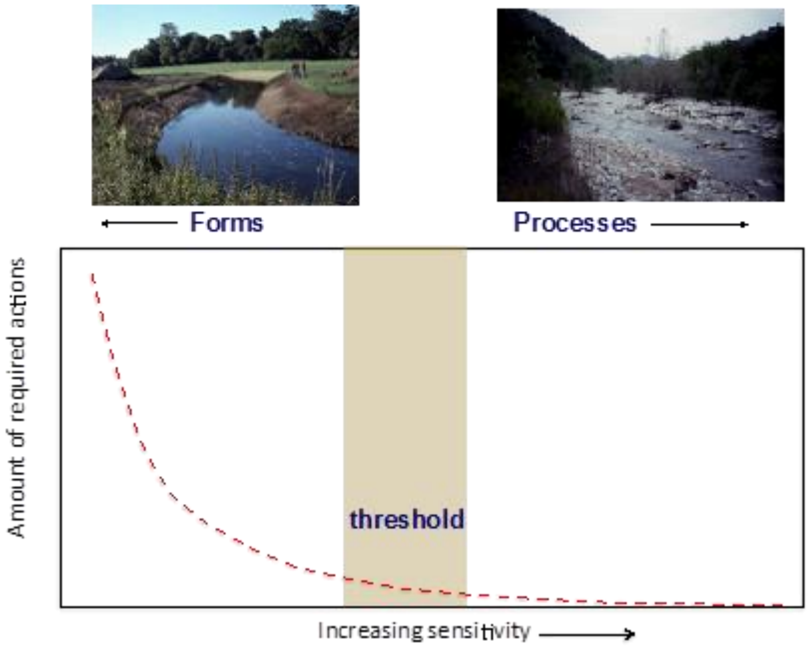


Figure 5.2 Schematic diagram showing the choice of 'process-based' vs. 'form-based' actions based on a hypothetical trend of sensitivity.

Many different terms have been proposed to describe the sensitivity of a river to changes in formative processes and also the way in which a river's morphology responds to these changes (Table 5.1).

Table 5.1 Summary of main terms and concepts that refer to the tendency of a river to change.

Concept (alternative term)	Definition	Key references
Sensitivity (Reactivity)	Measures of river sensitivity to change are considered to reflect the vulnerability (susceptibility) of any given river type. They indicate the ease with which adjustment can take place and the proximity to threshold conditions. Morphological responses to the same disturbance events are likely to be more pronounced along more sensitive reaches. River sensitivity is dictated to some degree by the river characteristics (e.g., river type, confinement, valley type, etc.), the within-catchment position of the reach and patterns/rates of geomorphic linkages (i.e., off-site impacts). *Sensitive rivers* adjust rapidly to perturbations and are prone to dramatic adjustments such as the breaching of thresholds, even when perturbations are relatively modest. Thus the degree of sensitivity of a river can be conceptualised as a quotient of the magnitude of channel response (the numerator) and the magnitude of change in the drivers that cause the response (the denominator).	Downs and Gregory (1995), Fryirs (2003), Brierley and Fryirs (2005), Downs et al. (2013)
Resilience	Resilience is the capacity of a system to respond to a perturbation or disturbance by resisting damage and recovering quickly. In contrast to sensitive rivers, *resilient rivers* have an inbuilt capacity to respond to disturbance via mutual adjustments that operate through negative feedback mechanisms.	Brierley and Fryirs (2005)
Vulnerability (Susceptibility)	Refers to the potential of a reach to experience a shift in state within its natural capacity for adjustment or to be transformed to a different type of river. Vulnerability can result from the breaching of either an intrinsic or an extrinsic threshold.	Brunsden and Thornes (1979), Schumm (1991), Brierley and Fryirs (2005), Downs et al. (2013)
Channel changes (Channel adjustments)	Channel changes or adjustments are changes in channel form induced by erosional and depositional processes (including bed incision or degradation, aggradation, narrowing, widening, lateral migration, avulsion).	Lane (1955), Schumm (1977), Shields et al. (2003), Brierley and Fryirs (2005)
Stability / Instability	Channel *stability* indicates a balance between applied forces and boundary resistance leading to stability or a 'dynamic equilibrium' in channel dimensions. Conversely, channel *instability* is determined by an imbalance between applied forces and boundary resistance. Channel instability is manifested by a series of processes determining an *adjustment* of channel form (including incision or degradation, aggradation, narrowing, widening, lateral migration, avulsion) occurring at a sufficiently wide spatial scale and within a sufficiently long temporal scale (at least 10 – 15 years).	Lane (1955), Schumm (1977), Shields et al. (2003)
Trajectory of change	The pathway along which a reach adjusts following disturbance. The term river *behaviour* has a similar but narrower meaning. It is used to indicate a sequence of geomorphic adjustments over time periods during which flow, sediment regimes and vegetation interactions remain relatively uniform.	Brierley and Fryirs (2005)
Recovery	Trajectory of channel change towards an improved condition.	Brierley and Fryirs (2005)
Morphological potential (Recovery potential)	The capacity of a given reach to self-adjust its morphology if left alone, or following some disturbance or restoration intervention.	Brierley and Fryirs (2005)

5.1.1 Assessment of river sensitivity

Assessment of a river's sensitivity provides an indication of the nature, extent and rate of potential channel changes that may occur within a given reach. The concept of sensitivity has been used by many researchers in relation to many aspects of river morphodynamics, including: (i) classification of channel adjustments (e.g., Downs and Gregory, 1993); (ii) response to human activities and natural events (e.g., Downs et al., 2013); (iii) exceedance of thresholds during high magnitude events (e.g., Harvey, 2001); (iv) definition of channel migration or erodible corridors (e.g., Rapp and Abbe, 2003; Piégay et al., 2005).

Various types of channel changes can contribute to an assessment of river reach-sensitivity, including: (i) lateral adjustments or migration, narrowing / widening, and changes in planform; (ii) vertical adjustments (e.g., incision, aggradation); (iii) changes in bed structure (e.g., armouring, clogging); (iv) changes in the types and assemblage of geomorphic units; (v) changes in riparian and aquatic vegetation extent, structure and biomass.

A catchment-wide procedure that leads to a relative assessment of sensitivity has recently been proposed by Reid and Brierley (2015) and has informed the methodology that is described below.

The assessment of sensitivity presented here is based on the outputs of the previous stages of the REFORM hydromorphological assessment framework. It starts with the classification of reaches according to their river type, and is followed by an evaluation of the trajectory of channel change at increasing levels of detail to describe or estimate the past extent and rate of channel adjustments. The sensitivity assessment procedure involves four phases of investigation and analysis (Figure 5.3). When river reaches are identified as sensitive (or reactive) at any phase of the analysis, further levels of detail are not necessarily required and the analysis can be concluded. Conversely, if there is not enough information to exit from the flow chart at any phase, additional levels of analysis are required. Such analyses can be integrated with the procedures described in the previous section (Stage II) to eventually identify reaches with a low sensitivity that are unlikely to respond to restoration based on supporting natural morphological recovery.

The assessment of reach sensitivity has **four phases**, which also reflect a hierarchical spatial analysis:
Phase (a) is typically carried out at the catchment scale, and is based on the classification of river types that are present across the entire river network.
Phase (b) is conducted only on alluvial mobile reaches. It requires an analysis of past changes based on secondary sources (e.g., aerial images). In some cases such an analysis may be constrained: for example, multitemporal analysis of remote sensing images is often difficult for small rivers.
Phase (c) is more onerous than the previous phases, and so is most likely to be applied to selected reaches representative of particular morphologies or river segments.
Phase (d) involves analysis of quantitative data and so is generally applied to selected reaches.

The **aims of the sensitivity assessment** can vary to some degree and can be conducted within different parts of the assessment framework. The combination of the first two phases (identification of river types and analysis of past changes) provides a catchment-wide assessment which indicates potentially sensitive reaches. This delimits portions of the fluvial network where possible actions might be concentrated and possible strategies (natural morphological change vs. morphological reconstruction) adopted. Phases c and d progressively focus on reaches that are representative of a particular river type or of some larger spatial unit (i.e. segment, landscape unit) in the catchment. The final phase of the analysis can be conducted in parallel with the reach-scale evaluation of the effects of specific actions during Stage IV.

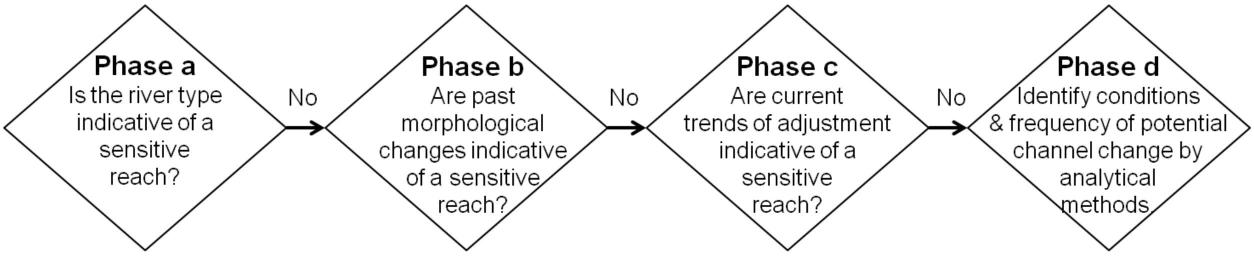


Figure 5.3 Flow chart summarising the sequence of 4 phases used to identify sensitive reaches.

Phase a: Assessment of sensitivity based on river typology

Spatial scale of assessment: catchment

A first assessment of sensitivity is based on the river type. The factors that control or are indicative of river channel response to disturbance (channel morphology, confinement, bed slope, sediment calibre, and characteristic geomorphic units) also determine the channel type. Therefore, application of the Extended River Typology (see REFORM Deliverable 2.1 and Stage I of this Deliverable) supports a preliminary assessment of the potential capacity of reaches for channel adjustment (Figure 5.4). Low sensitivity is generally associated with particular types of confined single-thread channel (bedrock, colluvial, alluvial cascade and step pool), because their confinement prevents lateral mobility, and vertical change is impeded or prevented by bedrock or coarse alluvial bed material. However, confined single-thread channels with a plane or riffle pool bed usually have a slightly higher capacity for adjustment of their bed. Unconfined single-thread, low energy rivers are also generally considered to have relatively low sensitivity, but this may be higher than the previous types and can only be assessed using information on their degree of past lateral mobility. Unconfined, high energy, braided or wandering rivers generally have high sensitivity and so river reaches of these types can leave the flow chart at this first phase (Figure 5.3), although the analyses conducted in subsequent phases may be useful since they provide a more detailed assessment of the nature of that sensitivity in terms of the nature and rates of changes that have occurred and the potential proximity to some threshold condition.

For *artificially fixed rivers* that are located in a partly confined or unconfined valley setting but where the banks are largely fixed artificially, the planform is not meaningful for assessment of sensitivity. For example, an artificially fixed straight reach with few or no bars cannot be typed and classified based on its planform because this is the result of channelization and so is very unlikely to represent the morphology that the river would exhibit if it was free to adjust. In such cases, more specific investigations should be conducted during the following phases.

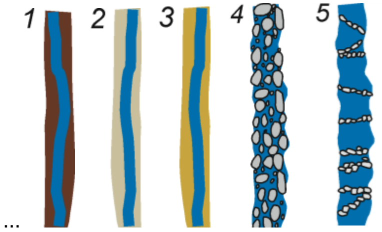
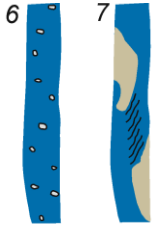
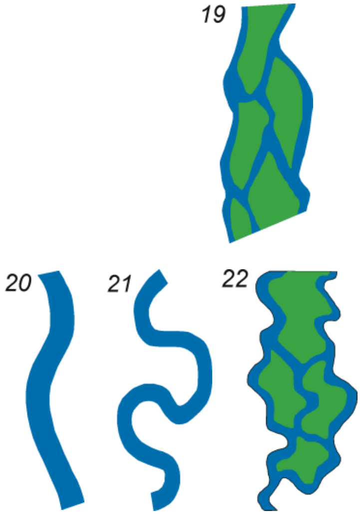
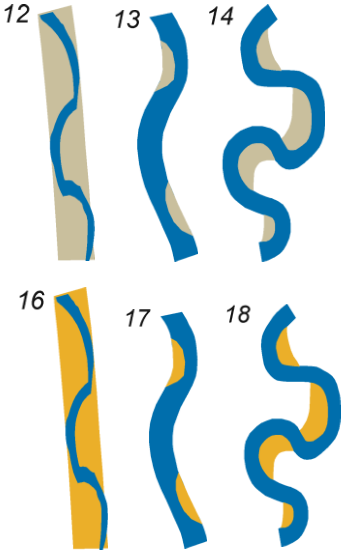
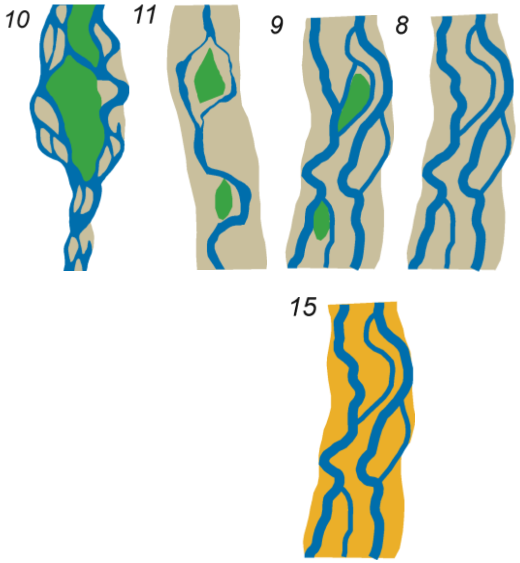
	Low	Medium	High
Confined single-thread (bedrock, colluvial, alluvial)			
Alluvial (in most cases partly confined or unconfined; wandering and multi-thread can be also confined)			

Figure 5.4 Classification of River Type Sensitivity as result of *Phase (a)*. For the definition of River Types see Table 3.4.

Phase b: Assessment of sensitivity based on past changes

Spatial scale of assessment: alluvial reaches with particular reference to partly confined and unconfined, relatively large reaches.

The assessment of temporal changes forms the basis for a more detailed, reach-scale evaluation of the actual capacity for channel adjustments. A given river type exhibits a potential range of adjustments which may vary depending on the specific variables determining the response. This can be assessed by an analysis of the past trajectory of change and contemporary trends of adjustment.

The assessment of past temporal changes performed during Stage II provides the information required for this analysis. In this phase, we employ methods that can assess historical trends of channel adjustment (a time frame of the order of 100 – 200 years). The assessment should include all the components of possible morphological adjustments: (i) bed elevation change; (ii) changes in planform morphology and channel migration; (iii) cross-sectional changes. To achieve such an assessment, an integrated analysis of information extracted from multi-temporal maps, aerial photographs, and satellite images is used to quantify changes in lateral channel mobility, channel width and planform, whereas an analysis of any available topographic surveys contributes to identifying changes in river longitudinal profiles, cross-sections and bed elevation. Finally, changes in morphological units characterizing a given river type or planform pattern, including the units in the riparian corridor, can be achieved using aerial photographs and map evidence. Analysis of past changes expands the initial assessment based on river type to incorporate information on the *rate*, *extent* and *nature* of changes that have occurred in the past at the reach scale. These changes can then be categorised as: *negligible*; *moderate*; or *large* changes so that the sensitivity assessment of the river network can be extended from phase a to display a ranked pattern of reach sensitivity at the catchment scale.

For those reaches where past changes are not observed or are negligible, it is necessary to move to phase c of the flow chart (Figure 5.3) to investigate potential adjustments and trajectories of change in more detail and at a finer scale.

Reaches that have been shown to have experienced significant amounts of change in the past, can be classified as sensitive and may exit from the flow chart at this phase, because it is possible to define the expected rates of adjustments from the reconstruction of the evolutionary trajectories within phase b. However, the contemporary trends of adjustments investigated in phase c (i.e., the last 10 – 20 years) can add important information and are probably more meaningful when defining the future rates of adjustment in the shorter term, although historical trends can indicate a range of possible rates on a longer time scale. In addition to the rate of adjustment, other information on the potential type of change can be extracted by identifying abrupt changes in the past that may be associated with the exceedance of a geomorphic threshold (e.g., avulsions, change from multi-thread to single thread channels, etc.).

In the case of *artificially fixed rivers*, it is necessary to identify the river type prior to the channelization intervention. If the channelization is recent (i.e. within the last few decades), information on the pre-channelization morphology is particularly meaningful, and an analysis of the trajectory of changes before channelization can be sufficient to define sensitivity. Where the channelization occurred in historical times, reconstruction of the pre-channelization morphology is likely to be difficult and is unlikely to be representative of the contemporary morphology that would occur in the absence of channelization. In either case, a more accurate analysis of the potential capacity for adjustment is necessary, as is performed in phase c, and an evaluation of potential rates and/or possible exceedance of geomorphic thresholds can be evaluated in phase d.

Phase c: Assessment of sensitivity based on contemporary trends of adjustment

Spatial scale of assessment: selected reaches.

After ranking sensitivity of reaches at the catchment scale, alluvial reaches classified as having 'low sensitivity' are further investigated. This phase also provides additional important information on rates of adjustment for those reaches which have already been classified as 'sensitive' and so should be conducted on at least some representative reaches.

Contemporary trends of channel adjustment refer to a short time scale (typically the last 10 – 20 years) compared to the longer-term changes assessed in the previous phase. They identify ongoing trends of adjustment and contemporary instability processes, which can differ from those which have occurred over the historical time scale. Two important points should be borne in mind when undertaking these analyses: (i) wherever possible, analysis and interpretation of past changes should take account of the presence, spatial extent, and age of artificial constraints that may have impeded or limited the range of changes; (ii) for relatively large rivers, aerial photos (and other remotely sensed data) can be conveniently used to conduct a multi-temporal analysis of changes, but it is difficult to conduct reliable assessments of small streams from such sources.

Trends of contemporary channel adjustment can be assessed using a combination of sources of information (see Step 3 of Stage II), including available topographic surveys and remote sensing images from the last 10 – 20 years, but *field survey* is generally crucial for gaining information on recent changes and ongoing trends of adjustment.

Phase d: Quantitative assessment of sensitivity

Spatial scale of assessment: selected reaches

In the case of reaches with *artificially fixed channels* and those classified as having 'low sensitivity' in the previous phases, phase d is essential. However, phase d can be applied to other cases to better define threshold conditions, to better integrate the results of the analysis of trajectories of change, and to obtain additional information on possible temporal occurrence and rates of adjustment. This is particularly true at a later stage when some scenarios of possible interventions have been identified and their effects on channel morphology have to be assessed.

Phase d consists of a series of analytical tools to evaluate the potential capacity for adjustment of a given reach, depending on its hydraulic properties, channel geometry, bed and bank sediment calibre, including the following.

- *Critical conditions for incipient motion of bed material:* This assessment can be carried out for a range of discharges in order to evaluate the estimated frequency of flow events capable of triggering bed mobility.
- *Bank stability analysis:* Bank stability can also be evaluated for a range of discharges. Increasing levels of detail may be applied. For rivers where fluvial erosion is evaluated to be the dominant process affecting riverbanks, an assessment of critical conditions for incipient motion of bank material (similar to the analysis for bed material) is sufficient. For river reaches where mass failure is identified as a dominant type of process, bank stability models coupled with groundwater modelling are required.
- *Empirically-defined thresholds of channel pattern change:* A set of empirically defined threshold conditions developed to separate braiding from meandering channel patterns can also be applied at this phase. Annex G of Deliverable D2.1 (Empirically defined threshold conditions) provides details of such methods.

5.1.2 Evaluation of potential for morphological improvement

In this section the terms 'recovery potential', 'morphological potential', 'potential for morphological improvement', or 'morphological recovery' (see Table 5.1) are used as synonymous terms indicating the potential capacity of a river reach to self-adjust its morphology in a direction that would improve its geomorphic condition and promote ecosystem functioning. The reference time scale implicit in the definition of morphological potential is of the order of the next 50-100 years, i.e. a significant time scale for future management.

Sensitivity is not the only characteristic determining the potential of a river reach to change its morphology and enhance its functionality and condition. This is also dictated by other factors, mainly the evolutionary trajectory of change that determines current morphological conditions, and the within-catchment position of the reach that takes account of off-site impacts and limiting factors. These aspects need to be integrated with sensitivity in order to define the potential for changes within a reach, as follows.

Evolutionary trajectory and current geomorphic condition

Together with defining reach sensitivity, it is important to consider the current geomorphic condition that is determined by the past evolutionary trend. This aspect can be evaluated on the basis of the information gained during previous stages.

Two aspects of the evolutionary trajectory are of particular relevance: (1) the type of evolutionary trajectory, i.e. the current trends in the context of the long-term changes; (2) the amount of changes and the exceedance of any geomorphic thresholds.

(1) Type of evolutionary trajectory. Current trends of adjustments (last 10-20 years) need to be placed in the context of the long-term evolution (e.g., last 100 – 200 years) for this type of evaluation. For example, if the long-term trajectory is of channel degradation (e.g., incision and narrowing) but the recent trend is the opposite (e.g., aggradation and widening), the reach has a good potential to further recover some of the functionality that has been altered during the long-term degradational phase. In this case, the potential for morphological improvement can be very high, and any morphological rehabilitation action should be designed to maximise the morphological benefits associated with the current trend of adjustment.

Many types of trajectories of change may exist. Some examples of evolutionary trajectories are described in Table 5.2 and are illustrated schematically with respect to two key parameters (bed elevation and channel width) in Figure 5.5. Combinations of these four cases or other types of trajectories are obviously possible.

Table 5.2 Current geomorphic conditions and morphological potential of the four trajectories considered in Figure 5.5.

Evolutionary trajectory	Description	Current geomorphic conditions	Morphological potential
T1. Long-term dynamic equilibrium	The reach has not experienced significant adjustments in the long term and remains in a condition of dynamic equilibrium.	Good	Functionality is very high and there is no need for morphological improvement
T2. Degradational trajectory	The reach has experienced one or more phases of adjustment and current trends indicate a continuation of this trajectory.	Poor	Morphological potential is relatively low because the trend is towards further deterioration of functionality
T3. Degradational trajectory with inversion of trend	The reach has experienced one or more phases of adjustment, but current changes indicate an inversion of trend.	Poor	Morphological potential is relatively high because the trend is towards an improvement of functionality
T4. Long-term stable trajectory	The reach has been artificially fixed since historical times and is therefore maintained in a condition of static stability.	Very poor	Morphological potential cannot be evaluated on the basis of the trajectory

The examples of trajectories *T2* and *T3* in Figure 5.5, consisting of one or more phases of adjustment, have been documented in various dynamic European rivers (e.g., in France: Liébault and Piégay, 2001, 2002, Italy: Rinaldi, 2003; Surian and Rinaldi, 2003; Surian et al., 2009; Poland: Wyżga, 1993, 2008; Spain: Garcia-Ruiz et al., 1997; Rovira et al., 2005; United Kingdom: Winterbottom, 2000).

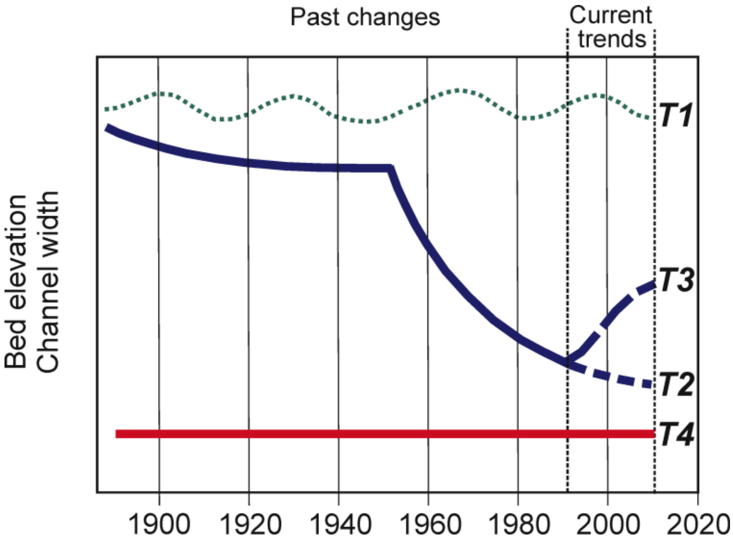


Figure 5.5 Classification of some main types of evolutionary trajectories.

(2) Amount of change and exceedance of geomorphic thresholds. Current conditions and the potential for morphological improvement are strongly related to the amount of change that has occurred during a given evolutionary trajectory. Morphological potential can be even lower when some geomorphic threshold has been exceeded and the river reach has experienced drastic morphological changes causing a complete modification that is deemed to be 'irreversible' (Brierley and Fryirs, 2005). For example, an alluvial reach downstream from a dam that has experienced severe bed level lowering to the bedrock, shows a drastically reduced diversity of geomorphic units, modified substrate characteristics, and disrupted lateral continuity because the floodplain has become a terrace.

Connectivity and position within the catchment

After having characterised the evolutionary trajectory and the amount of change, it is important to place the reach into its catchment context. Future adjustments and, therefore, the potential for morphological improvement can be strongly limited by factors and pressures that operate within the catchment, and their lagged and off-site impacts. Limiting factors include sediment supply and transport, the flow regime, vegetation dynamics, and human disturbances, which can be either internal or external to the reach. Consequently, the potential for morphological improvement of a given reach can be strongly influenced by adjustments occurring now and in the future along adjacent reaches, since an upstream migration or downstream progression of adjustments may occur, related to causes located beyond the reach.

Channel evolution of the investigated reach is strongly related to its *connectivity* with adjacent portions of the river network, and the position of the reach within the network dictates the effect of particular limiting factors and the connectivity of geomorphic processes. For example, the presence of natural or artificial barriers or other factors disrupting longitudinal continuity may limit the migration of the effects of off-site impacts. This may have beneficial or detrimental effects, depending on the current geomorphic conditions and the on-going trend of adjustments. For example, a reach that is in a good state and is isolated by upstream and downstream reaches, is likely to preserve its condition, whereas a similar reach that is well connected to downstream reaches where degradational processes are migrating upstream is likely to suffer deterioration in its condition.

Integration of sensitivity, current conditions and connectivity

Information obtained by investigating the trajectory of change and position within the catchment is integrated with the analysis of sensitivity to provide an overall evaluation of the potential for morphological improvement. This is useful for screening the general conditions at catchment scale, for supporting the setting of priorities in relation to spatial location, and for considering possible rehabilitation strategies. An open ended approach can be used for this assessment, which balances information on reach sensitivity, trajectory of change, and position within the catchment in a way that is appropriate for local circumstances. As an example, Brierley and Fryirs (2005) developed a decision tree to integrate assessments of geomorphic condition, river sensitivity, and position in a small Australian catchment in order to determine the recovery potential of a reach (Figure 5.6). Any such a decision tree would place more emphasis on reach sensitivity and trajectory of change and less on position within the catchment in a low gradient, low energy river environment, whereas position and longitudinal connectivity have very high relative importance in a steep, high-energy environment. A useful *output* of this integrated analysis is a map showing different classes of reach recovery potential at catchment scale (e.g. Figure 5.7).

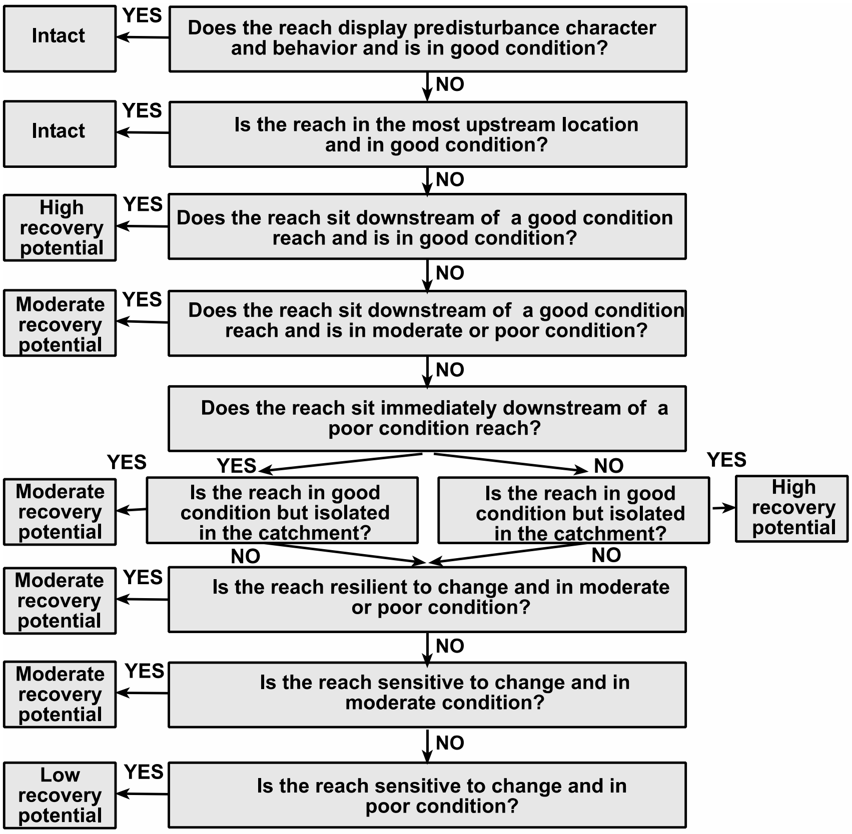


Figure 5.6 Example of decision tree for integrating information on sensitivity, current geomorphic condition and position in the catchment, to determine the recovery potential of a reach (from Brierley and Fryirs, 2005).

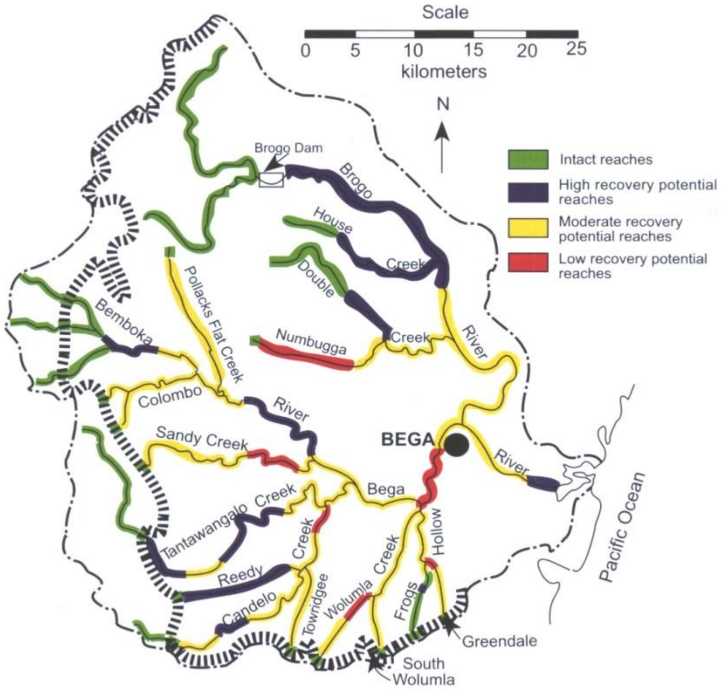


Figure 5.7 An example map of geomorphic recovery potential of reaches in the Bega catchment, Australia (from Brierley and Fryirs, 2005).

Main Outputs of Stage III - Step 1

- Summary Table and GIS mapping of sensitivity and morphological potential at catchment scale, with identification of most critical reaches, and of reaches with higher potential for improvement by supporting morphological changes

5.2 Step 2: Assess scenario-based future trends

After screening the portions of the catchment with higher potential for morphological improvement, step 2 focuses on assessment of possible future trends in morphological changes. Evaluation of future trends must be scenario-based. Scenarios can include continuation of present management and environmental conditions, one or more likely changes in management of the catchment, and/or changes in environmental conditions that are not necessarily related to factors at catchment scale (e.g., climate change). *Prediction of consequences* associated with each scenario builds on the spatial and temporal information assembled during the previous phases. For example, interpretation of channel changes and their causes conducted during Stage II is a key component in the projection of past and current trends of adjustments into the future.

Basic Questions of Stage III - Step 2

- What are the possible *future trends* in morphological changes?
- What are the possible *consequences* for fluvial processes, floodplain and channel morphology associated with a series of possible scenarios of changes in environmental or management conditions?
- What is a possible *spatio-temporal pattern* of future changes in the catchment?

Predictions of future changes may be qualitative or may employ modelling to produce more precise, quantitative forecasts. The following typology of models has been proposed by Darby & Van de Wiel (2003).
(1) *Conceptual models* provide qualitative descriptions and predictions of landform evolution.
(2) *Statistical and empirical models* generally establish functional relationships between dependent morphological variables and the independent driving variables (flow and sediment discharge).
(3) *Analytical models* are based on analytical equations describing and quantifying the various physical processes involved in the establishment of channel morphology.
(4) *Numerical models* are also based on governing equations describing the various physical processes involved but, differently from the previous category, they are solved by numerical algorithms, are multidimensional and capable of dealing with both spatial and temporal dimensions.
(5) *Physical models* consist of a replication in scale of the physical domain and of the processes involved.

Table 5.6 summarises the characteristics of each of the above categories of models. Selection of the type of modelling approach depends on various factors, such as the objectives of the modelling, the spatial and temporal scales, and the available data and resources.

Box 5.1: Conceptual models

Qualitative predictions can be supported by the use of *conceptual models*. Although conceptual models are qualitative, they support prediction of the possible future direction of changes and the dominance of different processes of adjustments.

One of the most recognized conceptual models in Fluvial Geomorphology is Lane's (1955) physical relationship between available sediment and available energy, commonly known as Lane's 'balance' (Figure 5.8). This model indicates stability of channel dimensions and can be mathematically expressed as the stream power proportionality:

$$Q\,S \propto Q_s\,D_{50}$$

where Q = discharge; S = bed slope; Qs = bed-material discharge; and D_{50} = median grain size of bed material, indicating that 50% of the bed material is finer.

The equation indicates that a change in any of these variables will tip the balance toward either aggradation or degradation; rebalancing can occur through compensating changes in one or more of the other three variables. If available stream power is augmented by an increase in the discharge or the gradient of the stream, there would be an excess amount of stream power relative to the discharge of bed-material sediment delivered from upstream. Additional sediment would be eroded from the channel boundary resulting in (1) an increase in bed-material discharge to an amount commensurate with the heightened stream power, and (2) a decrease in channel gradient and, consequently, stream power as the elevation of the channel bed is lowered. A similar response would be expected from a decrease in the erosional resistance of the channel boundary or a decrease in the size of bed-material sediment (assuming the bed is not cohesive). In contrast, a decrease in available stream power or an increase in the size or discharge of bed-material sediment would lead to aggradation of the channel bed. Aggrading or degrading channels represent end members on a continuum where vertical stability is represented at the center point.

The conceptual and semi-quantitative relation expressed by the Lane's equation is an enormous simplification, and provides a general starting point for thinking about how changes in Q and Qs might lead to adjustments within a river reach. However, the equation does not indicate where and how much erosion will occur and, therefore, how channel form might change.

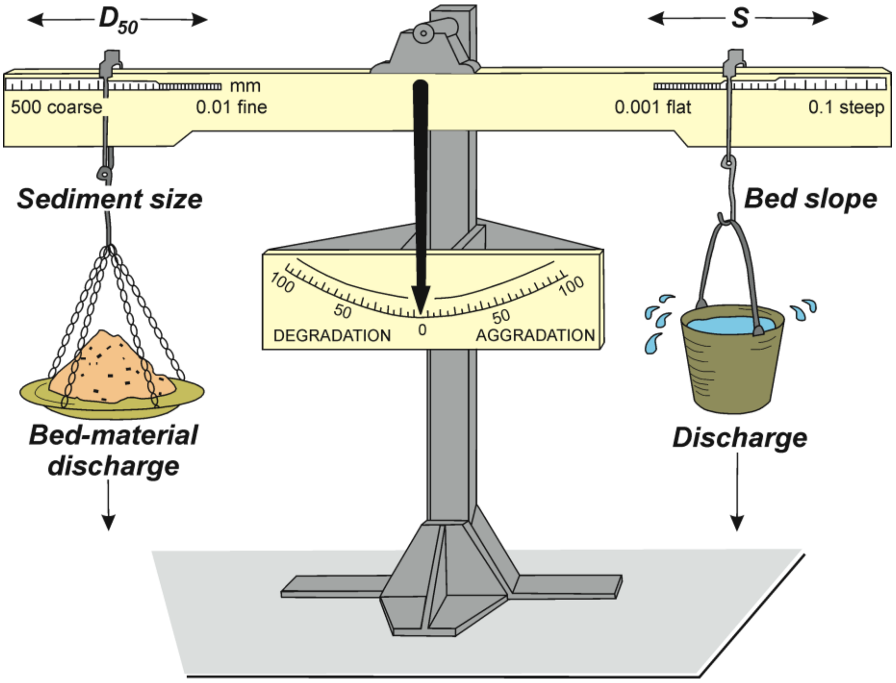


Figure 5.8 Lane's balance, one of the most recognized conceptual models and graphics in Fluvial Geomorphology (modified from Lane, 1955).

An extension of Lane's balance is the model of potential directions of adjustment proposed by Schumm (1977) (for more details see REFORM Deliverable D2.1, Chapter 9).

More advanced conceptual models combine spatial and temporal predictions by making use of *space-for-time substitution* (Schumm et al., 1984), also known as *ergodic reasoning*.

Alluvial channels destabilised by different natural and anthropogenic disturbances can systematically pass through a sequence of channel forms with time, even though the causal disturbances remain unchanged. The continuum of channel change can be conceptually segmented into discrete phases or stages, each characterised by the dominance of particular adjustment processes. These temporally and spatially organized adjustments are collectively termed channel evolution and permit reconnaissance-level interpretation of past, present, and future channel processes. Shifts in stages of channel evolution represent the crossing of specific geomorphic thresholds and the dominance of processes associated with those thresholds. Such models tend to be specific to particular environmental contexts, river types, and interventions; are informed by field observations; and describe temporal sequences of spatially complex responses that are generated by particular disturbances and propagate through the channel network.

An example of this type of model is the six-stage Channel Evolution Model (CEM) (Simon and Hupp, 1986; Simon and Rinaldi, 2013) (Figure 5.9), which describes a sequence of responses following channelization of a river and is a development of the five-stage model previously proposed by Schumm et al. (1984).

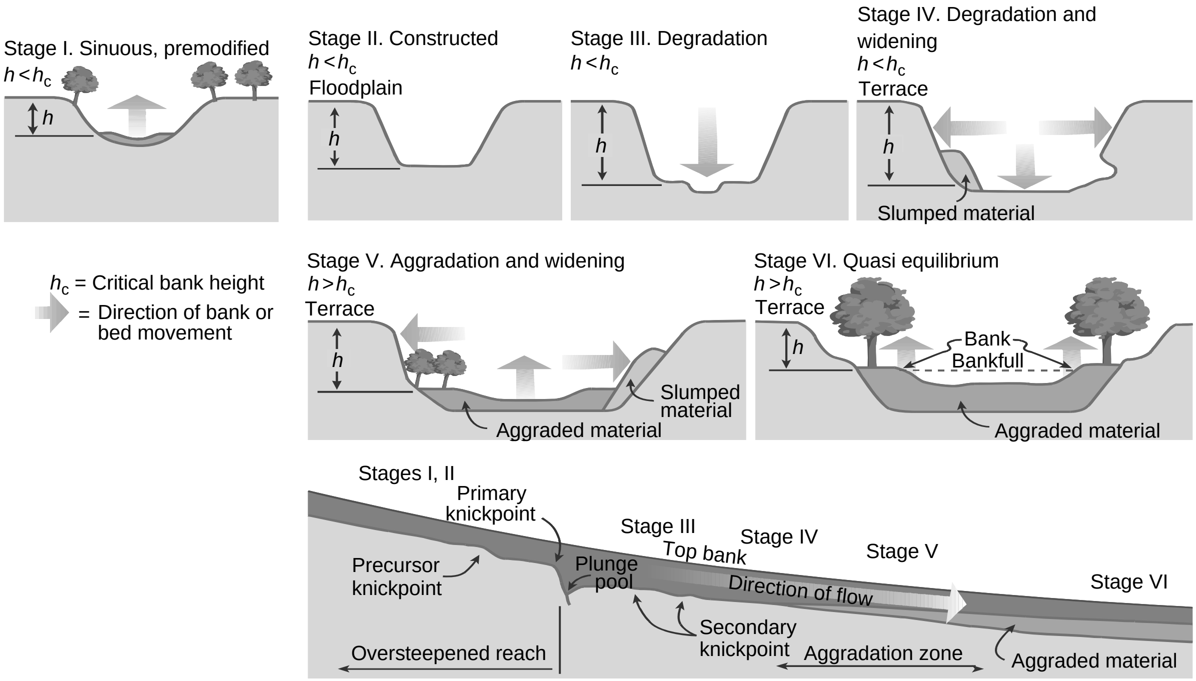


Figure 5.9 Six-stage Channel Evolution Model (CEM) originally developed by Simon and Hupp (1986) for channelized, single-thread streams with cohesive banks, disturbed by channelization.

CEMs were originally developed and have mostly focused on incised single thread channels with predominantly cohesive banks, and so their application to different geographic areas and contexts needs to be validated. However, Hawley et al. (2012) have proposed a five-stage CEM of semiarid stream response to altered hydrologic and sediment regimes associated with urbanization, which includes an evolutionary sequence incorporating a braided channel morphology. Furthermore, Cluer and Thorne (2013) have recently proposed a novel stream evolution model (SEM), which includes a premodified low-energy anabranching stage.

In the cases of braided or wandering, coarse-grained rivers and of a wider range of human pressures, as in many mountain or hilly areas of Europe (e.g., France, Italy, Poland, etc.), conceptual models should be adapted and based on empirical observations conducted on each specific catchment. For example, Bollati et al. (2014) developed a conceptual model of channel evolution (Figure 5.10) applied to an originally braided river (the Trebbia River, northern Italy), which was affected by a combination of human disturbances, including severe sediment removal. In this case, a phase of dominant incision and narrowing (stage II) was followed by a progressive inversion of the trends of channel width (stage III) and bed elevation (stage IV).

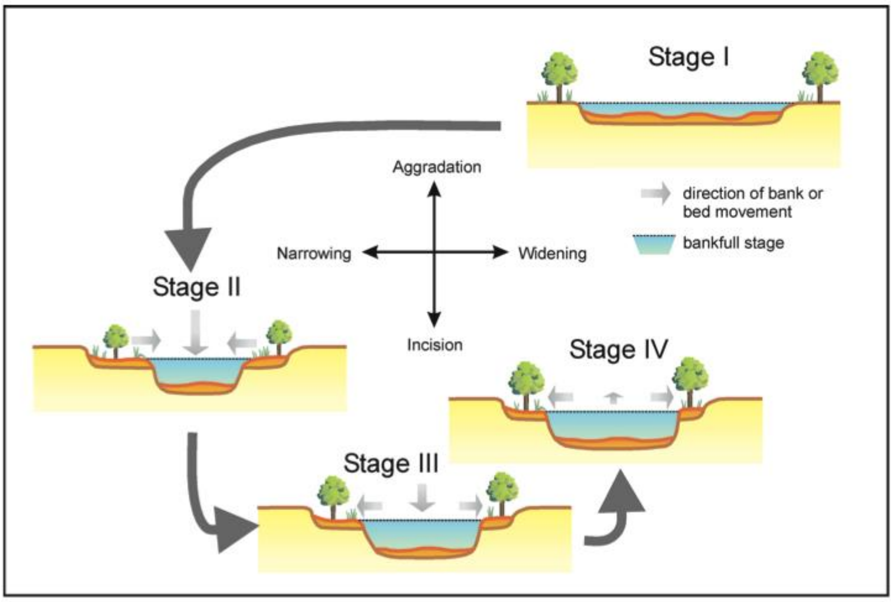


Figure 5.10 Four-stage channel evolution model developed for a braided, coarse-grained river (from Bollati et al., 2014).

Table 5.6 Summary of the characteristics, advantages and limitations of different categories of models (modified from Darby and Van de Wiel, 2003, and from Ziliani, 2011).

Model category	Typical applications	Advantages	Limitations	Model scale
1. Conceptual	Reconnaissance studies Qualitative forecasting Qualitative postdiction	Rapid assessment method – good for large areas and scoping studies Relatively simple – requires few resources and minimal background data	Requires basic training Qualitative results only	Conceptual models are available across a wide range of scales (from bar to catchment)
2. Empirical – statistical	Channel design Quantitative forecasting Quantitative postdiction Paleohydrology	Simple Input data are usually readily available	Site specific technique – care is required to avoid misapplication No information on rates of change Requires estimate of formative discharge Dimensionally inconsistent	Individual cross-sections representative of short river reaches
3. Analytical	Channel design Quantitative forecasting	Improved physical basis means these models are often valid across a range of environments Input data requirements are usually manageable	No information on rates of change Requires estimate of formative discharge Models can be quite complex	Individual cross-sections or short river reaches
4. Numerical	Channel design Quantitative forecasting	When calibrated, valid in a wide range of environments Provides detailed predictions of transient adjustments	Models are very complex and require specialist training Input data requirements are very large	In theory any, but heavily constrained by data requirements
5. Physical	Impacts of interventions Validation of numerical models	Maximum adherence to reality	Very high costs	Limited spatial contexts (site / reach)

The following *guidelines* summarise how the prediction of future trends may be tackled using the various approaches illustrated in the last two sections:
(1) the temporal scale should be the management scale, i.e., of the order of the next 50-100 years;
(2) at a first level of evaluation of consequences of selected scenarios, conceptual approaches based on empirical observations at the segment or reach scale are recommended, based on the reconstruction of the past trajectory of changes and the use of qualitative, conceptual models;
(3) the use of more advanced models should be aimed at evaluating possible trends of channel morphology rather than at predicting the exact channel geometry;
(4) numerical morphodynamic models could be included in this framework at a more detailed level, for example at the reach or sub-reach scale, and are more appropriate during the following stage of evaluation of effects of specific interventions.

One of the main outputs of this step is to produce a summary diagram illustrating the past evolution, current conditions, and possible future trends within a series of reaches representative of the various physical contexts of the catchment (e.g., upper mountain areas, middle portions, and lowland plain). A schematic example of this type of space – time diagram is shown in Figure 5.11.

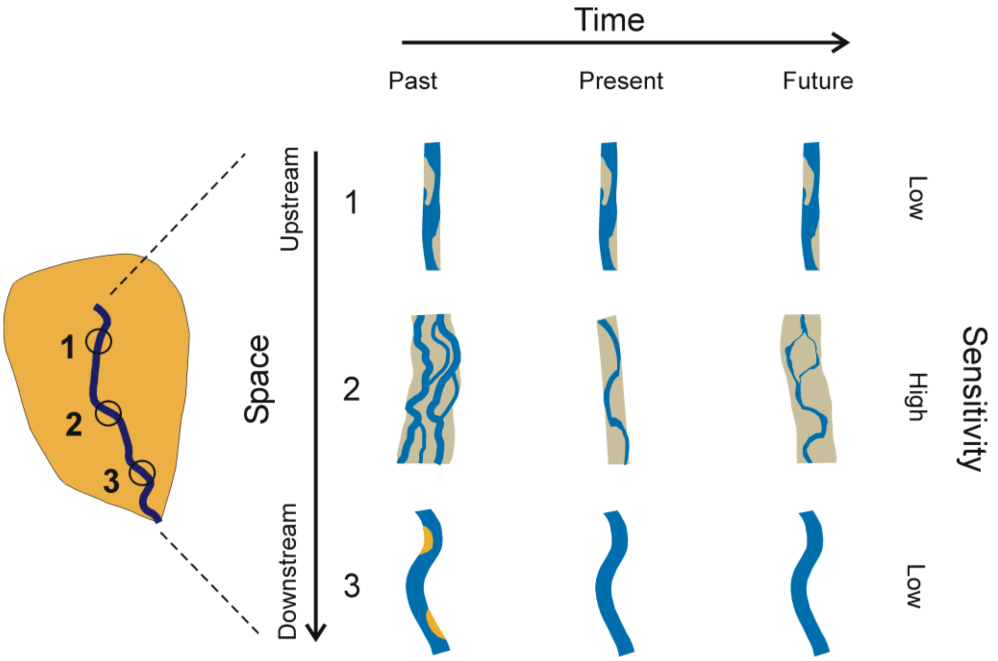


Figure 5.11 Sketch illustrating past, present, and future conditions in different sections of the catchment.

Main Outputs of Stage III - Step 2

- Summary Tables and diagrams illustrating past channel evolution, current conditions, and possible future trends

Links

- Procedures for assessment of sensitivity and morphological potential are also described in Brierley and Fryirs (2005) and in Reid and Brierley (2015).
- Models are reported in detail in **REFORM Deliverable D2.1** (Thematic Annexes) and in the **Part 2** of this Deliverable.

6. Stage IV: River management

This final stage uses the knowledge gained during the previous stages in relation to hydromorphological management and restoration. This knowledge must be placed in the wider context of REFORM WP5, where other aspects are considered in detail, such as identification of cost-effective measures promoting wider ecosystem and societal benefits, setting end-points for restoration projects, evaluation of success.

After assessing critical reaches and problems related to current conditions (Stage II), identifying reaches with a potential for morphological improvement and evaluating possible future trends related to some broad management scenarios (Stage III), this Stage provides a background to the selection and evaluation of hydromorphological actions.

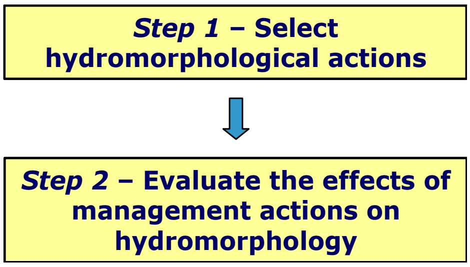


Figure 6.1 Steps of Stage IV.

6.1 Step 1: Select hydromorphological actions

In this step the focus is on actions that aim to improve physical processes and hydromorphological conditions. Although precise links between hydromorphological and ecological conditions are not well defined, a wide consensus exists that geomorphic dynamics and the functioning of natural physical processes spontaneously promote the creation and maintenance of habitats and ensure ecosystem integrity (Kondolf et al., 2003; Wohl et al., 2005; Florsheim et al., 2008; Fryirs et al., 2008; Habersack and Piégay, 2008). Therefore, enhancing hydromorphological quality is one of the main options to improve ecological conditions.

Basic Questions of Stage IV - Step 1

- What are the possible *actions* for enhancing physical processes and hydromorphological conditions of reaches that need to be improved?
- What are the *priorities* for interventions in terms of strategy (e.g., preservation vs. improvement) and in terms of position within the catchment?

Definition of the target conditions for a given river reach is fundamental for selecting the appropriate actions. The use of the concept of '**evolutionary trajectory**' of change (Figure 2.1) is key to defining target conditions (see Table 6.1). The knowledge of the evolutionary trajectory is based on the reconstruction of past channel changes and possible future trends obtained during the previous stages.

Table 6.1 Basic concepts related to hydromorphological restoration.

Basic concepts	Use
'Reference' hydromorphological conditions	Normally used to assess the degree of hydromorphological alteration of a given reach, i.e. its deviation from an unaltered, reference state.
'Target' conditions **and/or** ***'guiding image'***	Used to define restoration goals, i.e. provide the goal for the rehabilitation of reaches in poor condition.
'Past conditions'	During recent decades, many authors have moved away from using a *past condition* either as a reference or a target (e.g., Kern, 1992; Rhoads et al., 1999; Jungwirth et al., 2002; Brierley and Fryirs, 2005; Palmer et al., 2005; Dufour and Piégay, 2009). In several European countries, past conditions are not necessarily natural, e.g. 100-200 years ago sediment supply to river channels was higher than today due to intense deforestation and expanding crop production. Besides, past conditions are rarely achievable (e.g. climate has changed) and thus are of little practical use for river management, i.e. river restoration should not aim to recreate past conditions.
'Evolutionary trajectory' for setting hydromorphological restoration 'targets'	The awareness that a river follows a complex evolutionary trajectory, deriving from a combination of long-term trends and short-term fluctuations driven by both natural and human controls, implies that understanding past conditions and changes, causes, morphological alterations and processes determining current conditions, is fundamental in setting achievable and sustainable restoration goals.

Prioritization of restoration and management actions can be achieved in several ways, and is generally linked to other factors such as costs and other societal, political, and economic benefits (for these issues, see REFORM WP5 deliverables). If we focus on hydromorphological criteria only, current conditions together with the potential for morphological improvement are the key factors to prioritize restoration actions. Reaches having a higher morphological potential should be targeted before the most degraded reaches that require significant efforts and costs to recreate natural processes and forms.
The outputs of Stages II and III can provide the following information to support prioritization:
(i) identification of the best condition reaches so that they may be protected;
(ii) identification of critical reaches that may need some action for improving their conditions;
(iii) selection of critical reaches with a higher potential for morphological improvement;
(iv) selection of appropriate styles of restoration for the given spatio-temporal context in which the reaches to be improved are located.

Based on this knowledge, hydromorphological actions can be generally aimed to **two overall goals**:
(1) to **preserve** current ecological and/or hydromorphological conditions, when these conditions are evaluated as good;
(2) to **improve** current ecological and hydromorphological conditions through restoration actions, when these conditions are insufficient.

1. Preservation of current conditions
Reaches in good condition are generally located in the **upper portions of the catchment**, where they tend to be relatively distant from and mainly upstream of human disturbances. Although in good condition, particular consideration must be given to the **geomorphic conditions of adjacent reaches**, their distance from and connectivity with good condition reaches.
The **temporal component** must be also considered: a reach that is in good condition now could deteriorate in the future under the impact of space and time migration of adjustments. For example, when adjacent reaches are in poor condition, the investigated reach could be under threat of deterioration because of possible **migration of off-site impacts**, particularly when the adjacent reaches are well connected with the reach that is on good condition.
Reaches under threat of instability and with a highly susceptible to disturbance should have a **higher priority for preservation** of current condition, compared to distant or disconnected reaches.

2. Improvement of current conditions
Where **reaches are classified as 'poor'**, some type of action aimed to improve their hydromorphological condition may be needed.
In the case of reaches with a **high morphological potential for improvement**, actions directed towards **reactivation of processes and self-adjustments** should be preferred to morphological reconstruction or habitat enhancement actions.
Severely incised or channelized reaches in agricultural and urban, lowland areas have generally a low potential for natural morphological improvement, and should be ranked with a low priority. If some improvement is absolutely necessary, restoration of processes and self-adjustments is usually not feasible, and some degree of **morphological reconstruction** is required.

Box 6.1: Using morphological assessment methods to support identification of potential actions

The application of a method for the assessment of hydromorphological quality is extremely useful to analyse in detail critical problems and causes of alteration, as well as to eventually identify unaltered processes and forms that need to be preserved.

As an example, the Morphological Quality Index (**MQI**) is suitable for this type of application because of its structure which incorporates a clear definition of the various components of the evaluation (functionality, artificiality, channel adjustments, or longitudinal continuity, lateral continuity, morphology, substrate, vegetation). The evaluation structure provides a rational framework that is useful for identifying and prioritizing management strategies and restoration actions (Rinaldi et al., 2013b). For example, a first obvious prioritization rule is to preserve current conditions for those indicators which are in class A and to consider possible actions for improving those indicators lying in classes B and C.

The use of polar diagrams can be helpful to visualise the results of the assessment in terms of critical problems (Figure 6.2). The first case (A and B) refers to a reach with strong alteration of functionality, but relatively few artificial elements: the main problems are related to past reduction of sediment availability (because of gravel mining), present alteration by interception of bedload, and consequent severe incision. Therefore possible actions should be oriented towards promoting a recovery of sediment supply and longitudinal continuity. The second case (C and D) refers to a channelized reach where artificial elements alter lateral continuity, morphology, substrate, and vegetation. Here, possible scenarios of intervention should consider the reduction of some of the artificial elements in order to improve morphological quality.

Box 6.1 (continued)

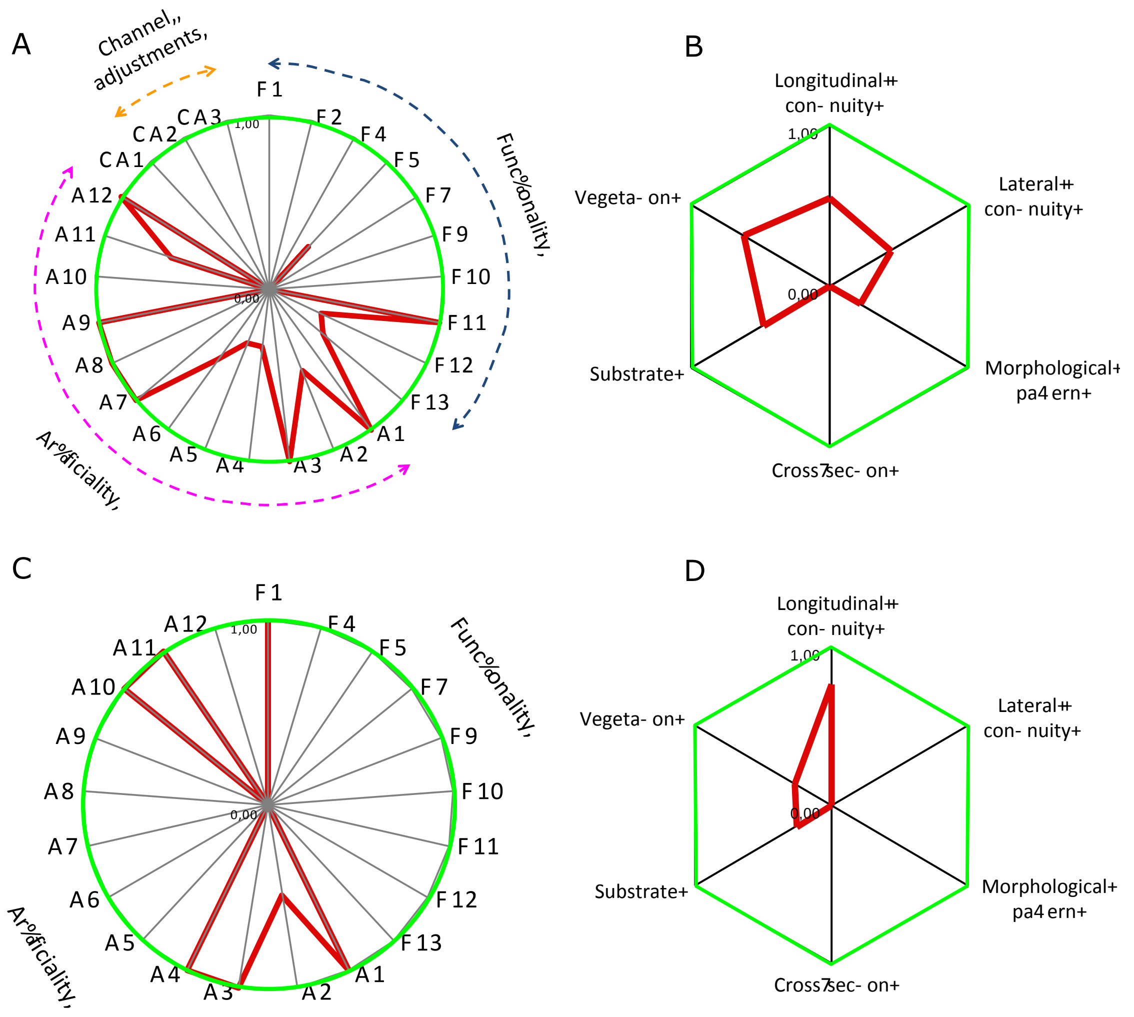


Figure 6.2 Application of a morphological assessment method (MQI) for supporting identification and prioritization of restoration actions. Green: maximum quality (reference conditions); Red: current conditions. For the list of indicators (F1, …, F13, etc.) see D6.2 Part 3.

Several **measures aimed at improving hydromorphological conditions** may be implemented. A short synthesis of the main categories of broad hydromorphological actions and their possible effects is reported in Table 6.1.

The following **main types of measures** can be considered (see the REFORM WIKI): (1) Water flow quantity improvement; (2) Sediment flow quantity improvement; (3) Flow dynamics improvement; (4) Longitudinal connectivity improvement; (5) River bed depth and width variation improvement; (6) In-channel structure and substrate improvement; (7) Riparian zone improvement; (8) Floodplains/off-channel/lateral connectivity habitats improvement; (9) Other aims to improve hydrological or morphological conditions. Each of these may have a series of beneficial and/or adverse effects on hydromorphology that need to be evaluated (Step 2).

Main Outputs of Stage IV - Step 1

- Definition of one or more scenarios of management actions or restoration interventions

6.2 Step 2: Evaluate the effects of management actions on hydromorphology

After identifying a series of possible scenarios of management and restoration actions, the effects of each of these must be evaluated. The hydromorphological evaluation must be included in a wider evaluation context, including ecology, ecosystem services, and various other socio-economical aspects.

Basic Questions of Stage II - Step 2

- What are the *effects* on physical processes and hydromorphological conditions of the actions identified in the previous step?
- Are these actions going to effectively enhance hydromorphological conditions? Are there possible adverse effects?

In this section we recall the main approaches that can be used to evaluate hydromorphological effects of the management actions selected in the previous step. Existing methods range from some qualitative evaluation to more quantitative analyses. Two main types of approaches can be identified: (1) application of hydromorphological assessment tools to qualitatively evaluate the benefits (or adverse effects) of planned restoration interventions; (2) quantitative modelling of the effects of restoration measures.

1. Application of hydromorphological assessment tools

Description

Many restoration projects tend to address symptoms at the local scale, omitting to understand the causes of the problem. Localised interventions have become the most common type of action adopted to address problems of habitat loss and morphological deterioration, and they are often implemented with no consideration of the physical processes responsible for the sustainability of these measures. However, evaluation of the hydromorphological effects of restoration projects needs to include an understanding on how engineering and management actions affect the physical processes operating at varying scales (e.g., site, reach, and watershed). For this reason, application of assessment methods to the pre- and post- restoration conditions can be an effective way to evaluate how the proposed actions may affect reach hydromorphology.

A tool that is particularly suitable for evaluating the effects of specific interventions is the **MQIm** (see **Part 3** and **Part 5**).

Advantages

Relatively simple to use; provides useful information on impacts in terms of the improvement or deterioration that a given intervention may have on the overall hydromorphological condition and on single components.

Limitations

Provides qualitative information; is not suitable to quantitatively evaluate the effects of an intervention on processes.

2. Modelling the effects of management or restoration actions

Description

The use of models is the most effective tool to evaluate and quantify the effects of a designed intervention on hydromorphological processes and channel morphology. Models represent a typical approach to making predictions of possible future trends (see Stage III, step 2), including the hydromorphological changes related to some specific action or intervention. Additionally, hydraulic and/or morphodynamic modelling allows the evaluation of possible adverse effects on flood risk. More details on models and their applications can be found in **Part 2** of this deliverable.

Advantages

Models provide a quantitative prediction of the possible physical effects of interventions.

Limitations

Models may be complex and may involve high implementation costs; the spatio-temporal scale of predictions is relatively short.

Main Outputs of Stage IV - Step 2

- Summary Tables and/or diagrams illustrating potential effects of proposed interventions on physical processes and overall hydromorphological conditions

Links

- The REFORM **Deliverable D5.1** Review of methodologies for benchmarking and setting end-points for restoration projects
- Identification of cost-effective measures promoting wider ecosystem and societal benefits, effects of climate and land use changes on river ecosystems and restoration practices, risks and uncertainty of different restoration strategies and option analysis are discussed in the **Deliverables D5.2, D5.3 and D5.4** of WP5.
- An additional, comprehensive tool that may be used to evaluate stream engineering, management and restoration proposals is the **RiverRAT** (Skidmore et al., 2011)

7 References

Alber, A., Piégay, H., 2011. Spatial disaggregation and aggregation procedures for characterizing fluvial features at the network-scale: application to the Rhône basin (France). Geomorphology 125, 343-360.

Alfredsen, K., Tesaker, E., 2002. Winter habitat assessment strategies and incorporation of winter habitat in the Norwegian habitat assessment tools. Hydrological Processes 16, 927–936.

Aparicio, M., Ballarín, D., Corrochano, A., Fernández Yuste, J.A., García Díaz, J., González Fernández, G., Horacio, J., Ibisate, A., Magdaleno, F., Vilán, X.M., Martínez Santa-María, C., Núñez, J.L., Ollero, A., Pérez Baviera, A., Puig, A. y Sánchez Martínez, F.J. 2015. Protocolo para la caracterización hidromorfológica de masas de agua de la categoría ríos en España. Actas del II Congreso Ibérico de Restauración Fluvial Restaurarríos 2015: 198-206. Pamplona.

Arnaud-Fassetta, G., 2003. River channel changes in the Rhone Delta (France) since the end of the Little Ice Age: geomorphological adjustment to hydroclimatic change and natural resource management. Catena, 51(2), 141-172.

Beechie, T.J., Sear, D.A., Olden, J.D., Pess, G.R., Buffington, J.M., Moir, H., Roni, P., Pollock, M.M., 2010. Process-based principles for restoring river ecosystems. BioScience, 60(3), 209-222.

Belletti, B., Dufour, S., Piégay, H., 2015a. What is the relative effect of space and time to explain the braided river width and island patterns at a regional scale? River Research and Applications, 31(1), 1-15.

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

Belletti, B., Rinaldi, M., Comiti, F., Nardi, L., Mao, L., Bussettini, M., 2015c. The Geomorphic Units survey and classification System (GUS). Proceedings I.S.Rivers, 2nd International Conference, June 22-26, 2015, Lyon, France.

Bollati, I.M., Pellegrini, L., Rinaldi, M., Duci, G., Pelfini, M., 2014. Reach-scale morphological adjustments and stages of channel evolution: the case of the Trebbia River (Northern Italy). Geomorphology, 221, 176-186, doi: 10.1016/j.geomorph.2014.06.007.

Boni, C.F., Mastrorillo, L., Petitta, M., 1993. Scomposizione della portata dei corsi d'acqua dell'Appennino Marchigiano con il metodo delle portate mensili caratteristiche. Geologia Applicata e Idrogeologia, 28, Bari, 121-129.

Bovee, K.D., Lamb, B.L., Bartholow, J.M., Stalnaker, C.B., Taylor, J., Henriksen, J., 1998. Stream Habitat Analysis Using the Instream Flow Incremental Methodology, Information and Technical Report USGS/BRD-1998-0004, 131 pp.

Bravard, J.P., Amoros, C., Pautou, G., Bornette, G., Bournaud, M., Creuzé Des Chatelliers, M., Gilbert, J., Peiry, J., Perrin, J., Tachet, H., 1997. River incision in south-easth France: morphological phenomena and ecological effects. Regulated Rivers: Research and Management 13, 75-90.

Brice, J.C., 1964. Channel patterns and terraces of the Loup Rivers in Nebraska. US Geol.Surv.Prof.Papers, 422D, 1-41.

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

Brierley, G.J., Fryirs, K.A., Boulton, A., Cullum, C., 2008. Working with change: the importance of evolutionary perspectives in framing the trajectory of river adjustment. 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. 65–84.

Brierley, G.J., Fryirs, K., Cullum, C., Tadaki, M., Huang, H.Q., Blue, B., 2013. Reading the landscape: integrating the theory and practice of geomorphology to develop place-based understandings of river systems. Progress in Physical Geography, 37(5), 601-621.

Brittain, J.E., Saltveit, S.J., 1989. A review of the effect of river regulation on mayflies (ephemeroptera). Regulated Rivers Research and Management, 3:191–204.

Brunsden, D., Thornes, J.B., 1979. Landscape sensitivity and change. Transactions of the Institute of British Geographers NS4, 463–484.

Bussettini, M., Percopo, C., Lastoria, B., Mariani, S., 2014. A method for characterizing the stream flow regime in Europe. In: Lollino, G., Arattano, M., Rinaldi, M., Giustolisi, O., Marechal, J.C., Grant, G.E. (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, 323-326.

Carolli, M., Vanzo, D., Siviglia, A., Zolezzi, G., Bruno, M.C., Alfredsen, K. 2015. A simple procedure for the assessment of hydropeaking flow alterations applied to several European streams. Aquatic Science, doi:10.1007/s00027-015-0408-5.

CEN, 2004. Water quality — Guidance standard for assessing the hydromorphological features of rivers. EN 14614:2004.

CEN, 2009. Water quality – Guidance standard on determining the degree of modification of river hydromorphology. European Committee for Standardization, EN 15843, Brussels, Belgium. 24 pp.

Cereghino, R., Lavandier, P., 1998. Influence of hypolimnetic hydropeaking on the distribution and population dynamics of Ephemeroptera in a mountain stream. Freshwater Biology, 40, 385–399.

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.

Chandesris, A., Malavoi, J.R., Mengin, N., Wasson, J.G., Souchon, Y., 2009. Hydromorphology auditing: a generalized framework at a nation scale to view streams and rivers in their landscape context. 7th ISE & 8th HIC Conference, Chile 2009, 9 pp.

Cluer, B., Thorne, C.R., 2013. A stream evolution model integrating habitat and ecosystem benefits. River Res. Appl. 30 (2), 135–154. http://dx.doi.org/10.1002/rra.2631.

Comiti, F., 2013. How natural are Alpine mountain rivers? Evidence from the Italian Alps. Earth Surface Processes and Landforms, DOI:10.1002/esp.2267.

Crowder, D.W., Diplas, P., 2002. Vorticity and circulation: spatial metrics for evaluating flow complexity in stream habitats. Canadian Journal of Fisheries and Aquatic Sciences 59, 633–645.

Cushman, R.M., 1985. Review of ecological effects of rapidly varying flows downstream of hydroelectric facilities. North American Journal of Fish Management, 5, 330–339.

Darby, S.E., Van De Wiel, M.J., 2003. Models in Fluvial Geomorphology. In: Kondolf G.M., Piégay H. (Eds), Tools in Fluvial Geomorphology, John Wiley & Sons Ltd, 503-537.

Downs, P.W., Gregory, K.J. 1993. The sensitivity of river channels in the landscape system. In Landscape sensitivity, Thomas, D.S.G., Allison, R.J. (Eds). Wiley: Chichester; 15-30.

Downs, P.W., Gregory, K.J., 1995. The sensitivity of river channels to adjustment. The Professional Geographer 47, 168–175.

Downs, P.W., Dusterhoff, S.R., Sears, W.A., 2013. Reach-scale channel sensitivity to multiple human activities and natural events: Lower Santa Clara River, California, USA: Geomorphology, 189, 121-134.

Dufour, S., Piégay, H., 2009. From the myth of a lost paradise to targeted river restoration: forget natural references and focus on human benefits. River Research and Applications 25, 568-581.

Dunbar, M.J., Alfredsen, K., Harby, A., 2012. Hydraulic-habitat modelling for setting environmental river flow needs for salmonids. Fish. Manage. Ecol. 19(6), 500-517.

Egozi, R., Ashmore, P., 2008. Defining and measuring braiding intensity. Earth Surface Processes and Landforms, 33(14): 2121-2138.

Fergus, T., 1997. Geomorphological response of a river regulated for hydropower: River Fortun, Norway. Regulated Rivers: Research & Management, 13(5), 449-461.

Fernández D., Barquin J., Raven P.J., 2011. A review of river habitat characterisation methods: indices vs. characterisation protocols. Limnetica 30(2):217–234

Fernández, J.A., Martínez, C., Magdaleno, F., 2012. Application of indicators of hydrologic alterations in the designation of heavily modified water bodies in Spain. Environmental Science & Policy (16), 31–43.

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

Freeman, M.C., Bowen, Z.H., Bove, K.D., Irwin, E.R., 2001. Flow and habitat effects on juvenile fish abundance in natural and altered flow regime. Ecol.Appl., 11, 179–190.

Frissell, C.A., Liss, W.J., Warren, C.E., Hurley, M.D., 1986. A hierarchical framework for stream habitat classification: Viewing streams in a watershed context. Environmental Management 10(2): 199-214.

Fryirs, K., 2003. Guiding principles for assessing geomorphic river condition: application of a framework in the Bega catchment, South Coast, New South Wales, Australia. Catena, 53(1), 17-52.

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.

García de Jalón, D., González del Tánago, M., Oglęcki, P., Wolter, C., Buijse, A.D., Parasiewicz, P., Piniewski, M., Tylec L., Acreman, M., Prudhomme, C., Okruszko, T., 2014, Influence of natural hydromorphological dynamics on biota and ecosystem function. REFORM Deliverable 2.2, Part 2.

Garcia-Ruiz, J.M., White, S.M., Lasanta, T., Marti, C., Gonzalez, C., Errea, M.P., Valero, B., Ortigosa, L., 1997. Assessing the effects of land-use changes on sediment yield and channel dynamics in the central Spanish Pyrenees. In: Walling, D.E., Prost, J.L. (Eds.), Human Impact on Erosion and Sedimentation. Proceedings of Rabat Symposium S6. IAHS Press, Publication no. 245, Institute of Hydrology, Wallingford, pp. 151 – 158.

Gilvear, D., Bryant, R., 2003. Analysis of aerial photography and other remotely sensed data. In: G.M. Kondolf, H. Piegay (Eds), Tools in fluvial geomorphology. J. Wiley, Chichester, 135-170.

Gonzàlez del Tànago, M., Garcìa de Jalòn, D., 2011. Riparian Quality Index (RQI): a methodology for characterizing and assessing environmental conditions of riparian zones. Limnetica, 30 (2): 235-254.

González del Tánago, M, Gurnell, A.M., Belletti, B. and García de Jalón, D. 2015. Indicators of river system hydromorphological character and dynamics: Understanding current conditions and guiding sustainable river management. Aquatic Sciences, First online, DOI: 10.1007/s00027-015-0429-0.

Gordon, N., McMahon, T., Finlayson, B., Gippel, C., Nathan, R., 2004. Stream hydrology: An introduction for ecologists, 2nd Edition, Wiley, 448 pp.

Gore, J.A., 1985. The restoration of rivers and streams: theories and experience. Butterworth/Ann Arbor, Michigan.

Grabowski, R.C., Gurnell, A.M., 2014. Case Study 1 - Hydromorphological assessment of the River Frome (UK): a lowland Northern European river. In: B. Blamauer, B. Belletti , D. García De Jalón, M. González Del Tánago, R.C. Grabowski,A.M. Gurnell, H. Habersack, M. Klösch, P. Marcinkowski, V. Martínez-Fernández, L. Nardi, T. Okruszko and M. Rinaldi (2014) Catchment Case Studies: Full Applications of the Hierarchical Multi-scale Framework. Deliverable 2.1, Part 3, of REFORM (REstoring rivers FOR effective catchment Management), a Collaborative project (large-scale integrating project) funded by the European Commission within the 7 Framework Programme under Grant Agreement 282656, 5-181.

Graf, W.L., 1977. The rate law in fluvial geomorphology. American Journal of Science 277: 178-191.

Gurnell, A.M., 1997. Channel change on the River Dee meanders 1946 to 1992 from the analysis of air photographs. Regulated Rivers: Research and Management 13: 13-26.

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

Gurnell, A.M., Downward, S.R., Jones, R. 1994. Channel planform change on the River Dee meanders, 1876-1992. Regulated Rivers: Research and Management 9: 187-204.

Gurnell, A.M., Peiry, J.L., Petts, G.E., 2003. Using historical data in fluvial geomorphology. In: G.M. Kondolf, H. Piegay (Eds), Tools in fluvial geomorphology. J. Wiley, Chichester, 77-101.

Gurnell, A.M., Surian, N. and Zanoni, L., 2009. Multi-thread river channels: a perspective on changing European alpine river systems. Aquatic Sciences 71: 253-265.

Gurnell, A.M., Belletti, B., Bizzi, S., Blamauer, B., Braca, G., Buijse, A.D., Bussettini, M., Camenen, B., Comiti, F., Demarchi, L., García De Jalón, D., González Del Tánago, M., Grabowski, R.C., Gunn, I.D.M., Habersack, H., Hendriks, D., Henshaw, A., Klösch, M., Lastoria, B., Latapie, A., Marcinkowski, P., Martínez-Fernández, V., Mosselman, E ., Mountford, J.O., Nardi, L., Okruszko, T., O'Hare, M.T., Palma, M., Percopo, C., Rinaldi, M., Surian, N., Weissteiner, C., Ziliani, L., 2014. A hierarchical 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., Belletti, B., Bizzi, S., Blamauer, B., Braca, G., Buijse, A.D., Bussettini, M., Camenen, B., Comiti, F., Demarchi, L., García De Jalón, D., González Del Tánago, M., Grabowski, R.C., Gunn, I.D.M., Habersack, H., Hendriks, D., Henshaw, A., Klösch, M., Lastoria, B., Latapie, A., Marcinkowski, P., Martínez-Fernández, V., Mosselman, E ., Mountford, J.O., Nardi, L., Okruszko, T., O'Hare, M.T., Palma, M., Percopo, C., Rinaldi, M., Surian, N., van de Bund, W., Weissteiner, C., Ziliani, L., 2015a. A multi-scale hierarchical framework for developing understanding of river behaviour. Aquatic Sciences, First online, DOI: 10.1007/s00027-015-0424-5.

Gurnell, A.M., O'Hare, M.T., Corenblit, D., Garcia De Jalon, D., Gonzalez del Tanago, M., Grabowski, R., Szewczyk, M., 2015b. A conceptual model of vegetation-hydrogeomorphology interactions within river corridors. River Research and Applications, early view, DOI: 10.1002/rra.2928.

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.

Habersack, H., Klösch, M., in prep. The Hydromorphological Evaluation Tool (HYMET). Intended for submission to Geomorphology.

Hauer, C., Habersack, H., 2009. Morphodynamics of a 1000- year flood in the Kamp River, Austria, and impacts on floodplain morphology. Earth Surface Processes and Landforms, 34(5), 654-682.

Hawley, R.J., Bledsoe, B.P., Stein, E.D., Haines, B.E., 2012. Channel evolution model of semiarid stream response to urban induced hydromodification. J. Am. Water Resour. Assoc. 48 (4), 722–744. http://dx.doi.org/10.1111/j.1752-1688.2012.00645.x.

Hearne, J., Johnson, I., Armitage, P., 1994. Determination of ecologically acceptable flows in rivers with seasonal changes in the density of macrophyte. Regulated Rivers: Research & Management 9, 177–184.

Heggenes, J., Wollebaek J., 2013. Habitat use and selection by brown trout in Streams. In: H.A. Maddock I., Kemp P. and Wood P. (Editor), Ecohydraulics: an integrated approach. John Wiley & Sons Ltd, 109-124.

Hooke, J.M., 2006. Human impacts on fluvial systems in the Mediterranean region. Geomorphology 79, 311-335.

Hughes, M.L., McDowell, P.F., Marcus, W.A., 2006. Accuracy assessment of georectified aerial photographs: implications for measuring lateral channel movement in a GIS. Geomorphology, 74(1), 1-16.

Huh, S., Dickey, D.A., Meador, M.R., Ruh, K.E., 2005. Temporal analysis of the frequency and duration of low and high streamflow: years of record needed to characterize streamflow variability, Journal of Hydrology 310, 78–94.

ISPRA, 2009. Implementazione della Direttiva 2000/60/CE - Analisi e valutazione degli aspetti idromorfologici. Versione 1.1. Istituto Superiore per la Protezione e la Ricerca Ambientale, Roma, 85 p.

Jacobson, R.B. 1995. Spatial controls on patterns of land-use induced stream disturbance at the drainage-basin scale--An example from gravel-bed streams of the Ozark Plateaus, Missouri. In: Costa, J.E., Miller, A.J., Potter, K.W. and Wilcock, P.R. (eds), Natural and Anthropogenic Influences in Fluvial Geomorphology, American Geophysical Union, Geophysical Monograph 89, pp. 219-239.

Jungwirth, M., Muhar, S., Schmutz, S., 2002. Re-establihing and assessing ecological integrity in riverine landscapes. Freshwater Biology 47, 867-887.

Kern, K., 1992. Restoration of lowland rivers: the German experience. In: Carling, P.A., Petts, G.E. (Eds.), Lowland Floodplain Rivers: Geomorphological Perspectives. John Wiley and Sons, Chichester, UK, pp. 279-297.

Kondolf, G.M., Smeltzer, M.W., Railsback, S.F., 2001. Design and performance of a channel reconstruction project in a coastal California gravel-bed stream. Environmental Management, 28(6), 761-776.

Kondolf, G.M., Piégay, H., Sear, D.A., 2003. 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, 633-660.

Kondolf, G.M., Piégay, H., Landon, N., 2007. Changes in the riparian zone of the lower Eygues River, France, since 1830. Landscape Ecology, 22, 367 – 384.

Łajczak, A., 1995. The impact of river regulation, 1850-1990, on the channel and floodplain of the Upper Vistula River, Southern Poland. In: Hickin, E.J. (Ed), River Geomorphology, John Wiley and Sons Ltd, pp. 209-233.

Lane, E.W. 1955. Design of stable alluvial channels. Transactions, American Society of Civil Engineers 120(2776):1234-1260.

Lane, S.N., Widdison, P.E., Thomas, R.E., Ashworth, P.J., Best, J.L., Lunt, I.A., Sambrook Smith, G.H., Simpson, C.J. 2010. Quantification of braided river channel change using archival digital image analysis. Earth Surface Processes and Landforms, 35(8), 971-985.

Large, A.R., Petts, G.E., 1996. Historical channel-floodplain dynamics along the River Trent: implications for river rehabilitation. Applied Geography, 16(3), 191-209.

Legleiter, C.J., 2012. Remote measurement of river morphology via fusion of LiDAR topography and spectrally based bathymetry. Earth Surface Processes and Landforms, 37(5), 499-518.

Liébault, F., Piégay, H., 2001. Assessment of channel changes due to long term bedload supply decrease, Roubion River, France. Geomorphology 36 (3–4), 167–186.

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.

Liébault, F., Lallias-Tacon, S., Cassel, M. and Talaska, N., 2013. Long profile responses of alpine braided rivers in SE France. River Res Appl 29 (10), 1253-1266. DOI: 10.1002/rra.2615.

Maddock, I., Harby, A., Kemp, P., Wood, P.J. (eds.), 2013. Ecohydraulics: An Integrated Approach. Wiley-Blackwell.

Magdaleno, F., Fernández-Yuste, J.A. 2011a. Meander dynamics in a changing river corridor. Geomorphology, 130(3), 197-207.

Magdaleno, F., Fernández, J.A., 2011b. Hydromorphological alteration of a large Mediterranean river: relative role of high and low flows on the evolution of riparian forests and channel morphology. River Research and Applications,27(3), 374-387.

Malavoi, J.R., Bravard, J.P., 2010, Elements d'hydromorphologie fluviale. ONEMA, Baume-Les-Dames, France, 224 pp.

Marcus, W.A., Fonstad, M.A., 2010. Remote sensing of rivers: the emergence of a subdiscipline in the river sciences. Earth Surface Processes and Landforms, 35(15), 1867-1872.

Martinez Santa-Maria, C., Fernández Yuste, J.A., 2010. IAHRIS 2.2. Indicators of Hydrologic Alteration in Rivers. Methodological Reference Manual & User’s Manual. http://www.ecogesfor.org/IAHRIS_es.html.

Martín-Vide, J.P., Ferrer-Boix, C., Ollero, A., 2010. Incision due to gravel mining: Modeling a case study from the Gállego River, Spain. Geomorphology, 117(3), 261-271.

Meile, T., Boillat, I.L., Schleiss, A.J., 2011. Hydropeaking indicators for characerization of the Upper-Rhone River in Switzerland. Aquatic Science, 73, 171-182.

Merritt, D.M., Scott, M.L., LeRoy Poff, N., Auble, G.T. and Lytle, D.A., 2010. Theory, methods and tools for determining environmental flows for riparian vegetation: riparian vegetation-flow response guilds. Freshwat. Biol., 55, 206-225.

Mount, N.J., Louis, J., Teeuw, R.M., Zukowski, P.M. and Stott, T. 2003. Estimation of error in bankfull width comparisons from temporally sequenced raw and corrected aerial photographs. Geomorphology 56: 65-77.

Murphey, J.B. and Grissinger, E.H. 1985. Channel cross-section changes in Mississippi’s Goodwin Creek. Journal of Soil and Water Conservation 40(1): 148-153.

Nanson, G.C., Croke, J.C., 1992. A genetic classification of floodplains. Geomorphology, 4(6): 459-486.

Nardi et al. (2015). Application of the Morphological Quality Index (MQI) to European case studies. D7.5 Conference Proceedings 'Novel Approaches to Assess and Rehabilitate Modified Rivers', 30 June - 2 July 2015, Wageningen (the Netherlands), 143-149.

Notebaert, B., Verstraeten, G., Govers, G., Poesen, J. 2009. Qualitative and quantitative applications of LiDAR imagery in fluvial geomorphology. Earth Surface Processes and Landforms, 34(2), 217-231.

Ollero, A., 2007. Channel adjustments, floodplain changes and riparian ecosystems of the middle Ebro River: assessment and management. Water Resources Development, 23(1), 73-90.

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., Ballarín, D., Díaz Bea, E., Mora, D., Sánchez Fabre, M., Acín, V., Echeverría, M.T., Granado, D., Ibisate, A., Sánchez Gil, L. y Sánchez Gil, N. 2008. IHG: un índice para la valoración hidrogeomorfológica de sistemas fluviales. Limnetica 27(1): 171-187.

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.

O'Neal, M.A., Pizzuto, J.E., 2011. The rates and spatial patterns of annual riverbank erosion revealed through terrestrial laser-scanner surveys of the South River, Virginia. Earth Surface Processes and Landforms 36(5): 695–701.

Oueslati, O., De Girolamo, A.M., Abouabdillah, A., Lo Porto, A., 2010. Attemps to flow regime classification and characterization in Mediterranean streams using multivariate analysis. International Workshop ‘Advances in Statistical Hydrology’; May 23-25, 2010, Taormina, Italy.

Palmer, M.A., Bernhardt, E.S., Allan, J.D., Lake, P.S., Alexander, G., Brooks, S., Carr, J., Clayton, S., Dahm, C.N., Follstad, S.J., Galat, D.L., Loss, S.G., Goodwin, P., Hart, D.D., Hassett, B., Jenkinson, R., Kondolf, G.M., Lave, R., Meyer, J.L., O'Donnell, T.K., Pagano, L., Sudduth, E., 2005. Standards for ecologically successful river restoration. Journal of Applied Ecology 42, 208-217.

Parasiewicz, P., Ryan, K., Vezza, P., Comoglio, C., Ballestero, T., Rogers, J.N., 2012. Use of quantitative habitat models for establishing performance metrics in river restoration planning. Ecohydrology 6(4), 668–678.

Parasiewicz, P., Rogers, J.N., Vezza, P., Gortazar, J., Seager, T., Pegg, M., Wiśniewolski, W., Comoglio, C., 2013. Applications of the MesoHABSIM Simulation Model. In: Maddock I., H.A., Kemp P. and Wood P. (ed.) Ecohydraulics: an integrated approach, John Wiley & Sons Ltd, 109-124.

Petit, F., Poinsart, D., Bravard, J. P., 1996. Channel incision, gravel mining and bedload transport in the Rhône river upstream of Lyon, France ("canal de Miribel"). Catena, 26(3), 209-226.

Petts, G.E., Müller, H. and Roux, A.L. 1989. Historical Change of Large Alluvial Rivers: Western Europe. Wiley, Chichester, UK.

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.

Platts, W.S., Megahan, W.F., Minshall, G.W., 1983. Methods for evaluating stream, riparian, and biotic conditions. US Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. Ogden, UT.

Poff, N.L., 1996. A hydrogeography of unregulated streams in the United States and an examination of scale-dependence in some hydrological descriptors, Freshwater Biology, 36, 71–91.

Poff, N.L., Ward, J.V., 1989. Implications of streamflow variability and predictability for lotic community structure: a regional analysis of Streamflow Patterns, Canadian Journal of Fisheries and Aquatic Sciences, 46, 1805–1818.

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.

Pyle, C.J., Chandler, J.H. and Richards, K.S 1997. Digital photogrammetric monitoring of riverbank erosion. Photogrammetric Record 15: 753-764.

Rapp, C.F., Abbe, T.B., 2003. A framework for delineating channel migration zones. Ecology Publication #03-06-027, Washington State Department of Ecology and Transportation, Olimpia, Washington, USA, 135 pp.

Raven, P.J., Fox, P., Everard, M., Holmes, N.T.H., Dawson, F.H. 1997. River habitat survey: A new system for classifying rivers according to their habitat quality. Freshwater Quality: Defining the Indefinable? In: Raven, P.J., Holmes, N.T.H., Charrier, P., Dawson, F.H., Naura, M., Boon, P.J. (2002) Towards a harmonized approach for hydromorphological assessment of rivers in Europe: a qualitative comparison of three survey methods. Aquatic Conserv: Mar Freshw Ecosyst 12(4):405-424.

Raven, P.J., Holmes, N.T.H., Charrier, P., Dawson, F.H., Naura, M., Boon, P.J. 2002. Towards a harmonized approach for hydromorphological assessment of rivers in Europe: a qualitative comparison of three survey methods. Aquatic Conserv: Mar Freshw Ecosyst 12(4):405-424.

Reid, H.E., Brierley, G.J., 2015. An approach to analysis of river sensitivity and its application to the Lower Tongariro River, New Zealand. In press.

Rhoads, B.L., 1995. Stream power. A unifying theme for urban fluvial geomorphology. In: Herricks, E.E. (Ed), Stormwater runoff and receiving systems, Lewis Publishers, Boca Raton, Fl., 65-75.

Rhoads, B.L., Wilson, D., Urban, M., Herricks, E.E., 1999. Interaction between scientists and nonscientists in community-based watershed management: emergence of the concept of stream naturalization. Environmental Management 24(3), 297-308.

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.

Richter, B.D., Baumgartner, J.V., Braun, D.P., Powell, J., 1998. A spatial assessment of hydrologic alteration within a river network. Regulated Rivers: Research & Management 14: 329-340.

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.

Rinaldi, M., Piégay, H., Surian, N., 2011. Geomorphological approaches for river management and restoration in Italian and French rivers. In: Simon, A., Bennett, S.E., Castro, J.M. (Eds) - Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses and Tools. Geophysical Monograph Series 194, American Geophysical Union, Washington D.C., USA, 95-113.

Rinaldi, M., Wyżga, B., Gurnell, A.M., Dufour, S., Bertoldi, W., 2013a. River processes and implications for fluvial ecogeomorphology: a European perspective. In: Shroder J. (Editor in chief), Butler D.R., Hupp C.R. (Eds), Treatise on Geomorphology, Academic Press, San Diego, CA, Vol.12, Ecogeomorphology, 37-52.

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

Rinaldi, M., Surian, N., Comiti, F., Bussettini, M., 2015. A methodological framework for hydromorphological assessment, analysis and monitoring (IDRAIM) aimed at promoting integrated river management. Geomorphology, http://dx.doi.org/10.1016/j.geomorph.2015.05.010.

Rovira, A., Batalla, R.J., Sala, M., 2005. Response of a river sediment budget after historical gravel mining (the lower Tordera, NE Spain). River Research and Applications 21, 829-847.

Saltveit, S. J., Halleraker, J. H., Arnekleiv, J. V., Harby, A., 2001. Field experiments on stranding in juvenile Atlantic salmon (Salmo salar) and brown trout (Salmo trutta) during rapid flow decreases caused byhydropeaking. Regulated Rivers Research and Management, 17, 609–622.

Schumm, S.A., 1977. The Fluvial System. John Wiley & Sons, New York, 338 p.

Schumm, S.A. (1991) To Interpret the Earth: Ten Ways to Be Wrong. Cambridge University Press, Cambridge.

Schumm, S.A., Harvey, M.D. and Watson, C.C. 1984. Incised Channels: Morphology, Dynamics and Control. Water Resources Publications, Littleton, Colorado, 200 pp.

Scorpio, V., Aucelli, P.P.C., Giano, S.I., Pisano, L., Robustelli, G., Rosskopf, C., Schiattarella, M. 2015. River channel adjustments in Southern Italy over the past

150 years and implications for channel recovery. Geomorphology, doi:10.1016/j.geomorph.2015.07.008.

Sear, D.A., Newson, M.D., Thorne, C.R., 2010. Guidebook of applied fluvial geomorphology. Thomas Telford Limited, London, UK, 257 pp.

Shen, Y., Diplas, P., 2008. Application of two- and three-dimensional computational fluid dynamics models to complex ecological stream flows. Journal of Hydrology 348, 195-214.

Shields, F.D. JR., Copeland, R.R., Klingeman, P.C., Doyle, M.W., Simon, A., 2003. Design for stream restoration. Journal of Hydraulic Engineering, 575-584.

Simon, A., 1989. A model of channel response in disturbed alluvial channels. Earth Surface Processes and Landforms 14:11-26.

Simon, A., 1992. Energy, time, and channel evolution in catastrophically disturbed fluvial systems. In: Phillips, J.D. and Renwick, W.H. (Eds), Geomorphic Systems: Geomorphology, pp.5: 345-372.

Simon, A., Hupp, C.R., 1986. Channel evolution in modified Tennessee channels. Proceedings, Fourth Federal Interagency Sedimentation Conference, Las Vegas, March 24-27, 1986: 2: 5-71 to 5-82.

Simon, A., Rinaldi, M., 2000. Channel instability in the loess area of the Midwestern United States. Journal of the American Water Resources Association 36(1): 133-150.

Simon, A., Rinaldi, M., 2013. Incised channels: disturbance, evolution and the roles of excess transport capacity and boundary materials in controlling channel response. In: Shroder J. (Editor in chief), Wohl E. (Ed), Treatise on Geomorphology, Academic Press, San Diego, CA, Vol.9, Fluvial Geomorphology, 574-594.

Simon, A., Castro, J., Rinaldi, M., 2015. Channel form and adjustment: characterization, measurement, interpretation and analysis. In: Kondolf, G.M., Piégay, H. (Eds), Tools in Fluvial Geomorphology, John Wiley and Sons, Chichester, UK.

Skidmore, P.B., Thorne, C.R., Cluer, B.R., Pess, G.R., Castro, J.M., Beechie, T.J., Shea, C.C., 2011. Science base and tools for evaluating stream engineering, management, and restoration proposals. U.S. Dept. Commer., NOAA Tech. Memo. NMFS-NWFSC-112, 255 p.

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.

Swanson, B.J., Meyer, G.A. and Coonrod, J.E. 2011. Historical channel narrowing along the Rio Grande near Albuquerque, New Mexico in response to peak discharge reductions and engineering: magnitude and uncertainty of change from air photo measurements. Earth Surface Processes and Landforms 36: 885-900.

Thorne, C.R., Russell, A.P.G., Alam, M-K., 1993. Planform pattern and channel evolution of the Bramaputra River, Bangladesh. In: Best, J.L. and Bristow, C.S. (eds), Braided Rivers, Geological Society Special Publication No.75, pp. 257-276.

Thorne, C.R., Allen, R.G., Simon, A., 1996. Geomorphological river channel reconnaissance for river analysis, engineering and management. Trans.Inst.Br.Geogr. NS21 469-483.

Toffolon, M., Siviglia, A., Zolezzi, G., 2010. Thermal wave dynamics in rivers affected by hydropeaking. Water Resources Research, 46, W08536.

Uribelarrea, D., Pérez-González, A., & Benito, G., 2003. Channel changes in the Jarama and Tagus rivers (central Spain) over the past 500 years. Quaternary Science Reviews, 22(20), 2209-2221.

UK Technical Advisory Group – UKTAG, 2008. UK Environmental Standards and Conditions (Phase 1) – Final. Vol. SR1-2006, 73 pp.

Valentin, S., Lauters, F., Sabaton, C., Breil, P., Souchon, Y., 1996. Modelling temporal variations of physical habitat for brown trout (Salmo trutta) in hydropeaking conditions. Regulated Rivers Research and Management, 12, 317–330.

Vezza, P., Parasiewicz, P., Spairani, M., Comoglio, C., 2014. Habitat modelling in high gradient streams: the meso-scale approach and application. Ecol. Appl. 24(4), 844-861.

Vezza, P., Muñoz-Mas, R., Martinez-Capel, F., Mouton, A., 2015. Random forests to evaluate biotic interactions in fish distribution models. Environ. Model. Software 67(0), 173-183.

Walker, K.F., Sheldon, F., Puckridge, J.T., 1995. A prespective on dryland river ecosystem. Regulated Rivers: Research & Management, 11, 85-104.

Ward, J.V., Stanford, J.A., 1979. Ecological factors controlling stream zoobenthos with emphasis on thermal modification of regulated streams. In: Ward, J.V., Stanford, J.A. (Eds), The Ecology of Regulated Streams, Springer, New York, 35-55.

Wilkes, M.A., Maddock, I., Link, O., Habit, E., 2015. A Community-Level, Mesoscale Analysis of Fish Assemblage Structure in Shoreline Habitats of a Large River Using Multivariate Regression Trees. River Res. Appl., Early View.

Williams, G.P., Wolman, M.G., 1984. Downstream effects of dams on alluvial rivers. U. S. Geological Survey Professional Paper 1286 83 p.

Wilson, K.V., Jr. and D.P. Turnipseed 1993. Channel-bed and channel-bank stability of Standing Pine Creek tributary at State Highway 488 at Free Trade, Leake County, Mississippi. U.S. Geological Survey Open-File Report 93-37, 20 p.

Wilson, K.V., Jr. and D.P. Turnipseed 1994. Geomorphic response to channel modifications of Skuna River at the State Highway 9 crossing at Bruce, Calhoun County, Mississippi. U.S. Geological Survey Water-Resources Investigations Report, 94-4000, 43 p.

Winterbottom, S.J., 2000. Medium and short-term channel planform changes on the Rivers Tay and Tummel, Scotland. Geomorphology 34: 195–208.

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 http://dx.doi.org/10.1029/2005WR003985.

Wolter, C., Buijse, A.D., Parasiewicz, P., 2015. Temporal and spatial patterns of fish response to hydromorphological processes. River Research and Applications, in press.

Wyżga, B., 1993. River response to channel regulation: case study of the Raba River, Carpathians, Poland. Earth Surface Processes and Landforms 18, 541–556.

Wyżga, B., 2001a. A geomorphologist’s criticism of the engineering approach to channelization of gravel-bed rivers: case study of the Raba River, Polish Carpathians. Environmental Management 28, 341–358.

Wyżga, B., 2001b. Impact of the channelization-induced incision of the Skawa and Wisłoka Rivers, southern Poland, on the conditions of over- bank deposition. Regulated Rivers: Research and Management 17, 85–100.

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.

Zawiejska, J., Wyżga, B., 2010. Twentieth-century channel change on the Dunajec River, southern Poland: Patterns, causes and controls. Geomorphology, 117(3), 234-246.

Ziliani, L., 2011. Ricostruzione e previsione dell’evoluzione morfologica di un alveo a fondo ghiaioso (F.Tagliamento): integrazione di modellazione numerica, analisi GIS e rilievi di terreno. Tesi di Dottorato, XXIII Ciclo, Università di Padova, 250 pp.

Zolezzi, G., Siviglia, A., Toffolon, M., Maiolini, B., 2010. Thermopeaking in Alpine streams: Event characterization and time scales, Ecohydrology, 4, 564-576.