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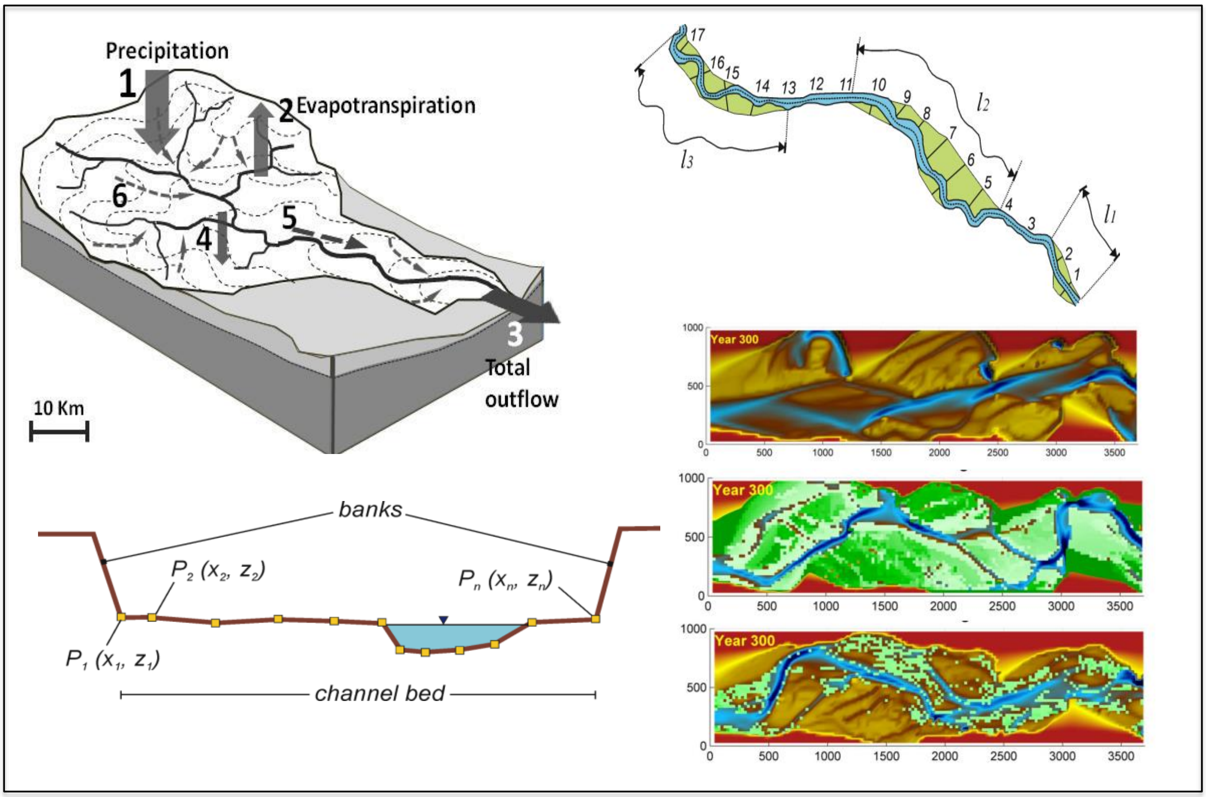
REFORM

REstoring rivers FOR effective catchment Management



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PP	Restricted to other programme participants (including the Commission Services)	
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Summary

Background and Introduction to Deliverable 6.2

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

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

The deliverable is structured in five parts. Part 1 provides an overall framework for hydromorphological assessment. Part 2 (this volume) 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 some case studies of some of the tools and methods reported in the previous parts.

Summary of Deliverable 6.2 Part 2

Part 2 of Deliverable 6.2 provides detailed information on some specific aspect outlined in Part 1.

In Annex A, a series of indicators is presented for the different stages of hydrological characterization, assessment of current status (alteration) and design (rehabilitation measures), including groundwater – surface water indicators.

Annex B reviews monitoring indicators, evaluation tools, and analyses which are suitable for monitoring morphological conditions.

Annex C reports monitoring protocols for riparian vegetation.

In Annex D, a summary of models used in hydromorphology is reported.

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ANNEX A Hydrological monitoring indicators

Martina Bussettini, Carlo Percopo, Barbara Lastoria and Giovanni Braca

ISPRA, Italy

Summary

In this document, a series of indicators is presented for the different stages of hydrological characterization, assessment of current status (alteration) and design (rehabilitation measures), starting from those already presented in REFORM Deliverable 2.1. Moreover, methods and indicators of groundwater - surface water interaction, highlighting the crucial role of GW-SW interaction in the hydrological response of the river system as a whole, are suggested.

The spatial scale we focus on is the river segment or reach, where we consider a certain discharge as uniform. The data needed for the assessment range from daily to hourly discharge time series and, for the purposes of design, groundwater levels or spring discharges.

For each group of indicators, the appropriate reference spatial scale and type of data is reported.

Glossary

Baseflow: The portion of stream discharge attributable to groundwater flowing from the "point source" or "linear springs" into the stream network; "baseflow is not attributable to direct runoff from precipitation or melting snow" (USGS, Glossary of Hydrologic terms).
Baseflow index: Ratio between baseflow and total discharge from a river section in a given time interval.
Catchment (or watershed) area: Drainage area, bounded by the line of the watershed, from which surface runoff is collected into the hydrographic network (also: Area of land draining into a stream at a given location, Chow *et al*., 1988).
Effective infiltration: Portion of infiltrated water that reaches the water table (saturated zone), and corresponds to the actual groundwater recharge (Kresic and Stevanovic, 2010).
Flow regime: Set of quantitative and temporal features of annual streamflow.
Groundwater flow: Water from effective infiltration which feed springs and streams through sub-surface pathways.
Hydrological cycle: Cycle of water flow into (precipitation), through (surface, soil and groundwater pathways) and from (streamflow) a catchment.
Infiltration: Water movement through the land surface into the subsurface (Kresic and Stevanovic, 2010).
Intermittent stream: Stream which does not support continuous surface flow.
Mean annual hydrological cycle: Typical (long-term) cycle of water flow into, through and from a catchment over at least a 20 year period.
Perennial stream: Stream that supports perennial flow; during dry periods, perennial streams are fed by groundwater.
Recharge area: Area in which water reaches the zone of saturation by surface infiltration (Heath, 1984).
Recharge of the aquifer: The process of addition of water to the saturated zone.
Surface Runoff: the portion of rainfall that flows over the land surface to the drainage network during rainfall events.
Temporary stream: stream that contains water only occasionally, for example, only during rainfall or snow melt.
Water budget: quantitative assessment of water volumes coming into and leaving a catchment or other water body (e.g. aquifer, lake) over a particular time period.
Water Resources: renewable water volumes yielded by gravity from hydrogeological units (Castany, 1982).. Usable water resources are only a portion of the total water resource, because they must allow for the water required to maintain the flow of perennial streams and the good status of surface ecosystems.

A.1 Indicators of hydrologic characterization

Spatial scale: *Segment/reach*
Type of data: *Daily river discharge series*

Hydrological characterization of a stream is based on the analysis of indicators of the response of the river basin to climatic (precipitation, air temperature), hydrogeological, geomorphological and land cover conditions.
The methodology for hydrological characterization is reported in D2.1, Part 2 Annex C – "*Flow regime analysis and Hydrological Alteration*", and in the D6.2 Main Report.
The relevant hydrological indicators are listed in Table A.1.

Table A.1 List of hydrological indicators.

Hydrological Indicators and assessed parameters (Poff, 1996)	**Assessment methods**
QMean Daily mean discharge, m^3/s	Time series of hydrological records (mean daily discharge recorded at a gauging station located at the outlet of the river segment or reach; at least 20 years of records are needed) usually derived from water level values recorded at gauging stations that are transformed into discharges using discharge/runoff - stage calibration curves. Starting from the listed characterization indicators (left column), a flow regime classification is applied, which determines the type of flow regime supported by the river segment or reach. The Flow regime classification method allocates streams to one of nine types based on the flow regime's: (1) intermittency/perennity; (2) groundwater-surface water interaction; (3) type of prevailing water sources that is feeding the river flows: (rainfall, snow and ice melt, groundwater seepage).
DAYCV – Daily discharge coefficient of variation, % Average (across all years) of ((the standard deviation of daily discharge within the year divided by the annual mean discharge) x 100).	
FLDFREQ – Flood frequency, 1/yr The average number of floods per year having a discharge higher than the mean of the annual maximum daily discharge (fixed flood threshold).	
FLDPRED – Seasonal flood predictability The maximum proportion of all floods over the fixed flood threshold that fall into one of six "60-day seasonal windows", divided by the total number of floods. It ranges from 0.167 (absence of seasonality) to 1 (complete predictability of floods).	
FLDTIME – Timing of floods; day The day number of the first day of the 60-day period when FLDPRED is highest. The first 60-day period is January-February and it includes February 29.	
BFI – Base Flow index, % Annual mean of the monthly ratios of the "minimum of monthly discharge" to the "mean monthly discharge", multiplied by 100	
ZERODAY – Extent of intermittency (number of days) The average number of days in a year having zero discharge	

The flow regime characterization identifies nine types of rivers on the basis of their flow:
- Intermittency;
- Groundwater contribution (e.g. baseflow);
- Prevailing water source (rainfall, snowmelt, groundwater).

The model used to define the flow regime types from the hydrological indicators is shown in Figure A.1.

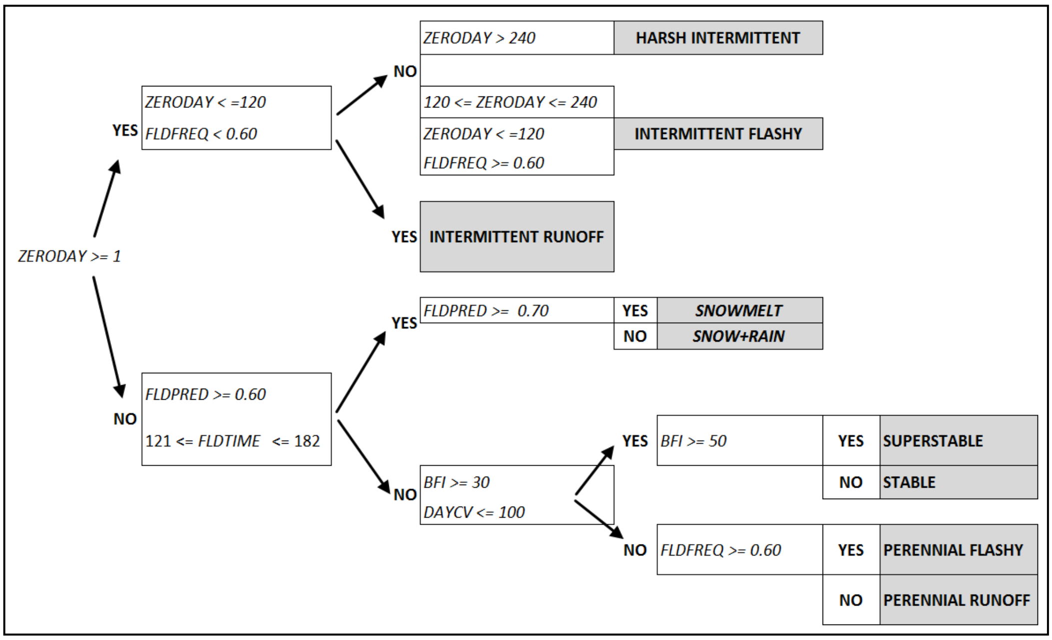

Figure A.1 Conceptual model of flow regime classification.

A.2 Indicators for the assessment of current status

Spatial scale: *Segment/reach*
Type of data: *Daily/hourly river discharge series*

The hydrological indicators are based on those deriving from the IHA method (D2.1, Part 2 Annex C, Section C.8), integrated with two indicators related to channel-forming discharge (Qp_2 and Qp_{10}), which make use of daily values of stream discharge, and with two specific indicators of hydropeaking (HP1 and HP2) estimated at the hourly (or sub-hourly) scale (Table A.2). These latter indicators have been introduced to take into account the **hydropeaking** phenomenon in terms of sub-daily flow fluctuations (HP1) and flow-ramping rate (HP2) (Carolli et al., 2015).

HP1 is defined as the median of the daily values of the difference between the maximum ($Q_{max,i}$) and the minimum ($Q_{min,i}$) daily discharge, divided by the mean daily discharge ($Q_{mean,i}$):

$$HP1_i = \frac{(Q_{max,i} - Q_{min,i})}{Q_{mean,i}} \quad i \in [0,365]$$

$$HP1 = \text{median } (HP1_i)$$

HP2 is the median of $HP2_i$, which is the 90% percentile of the change in discharge between two successive discharge observations, divided by the observation time interval.

$$(HP2_k)_i = \left(\frac{\Delta Q_k}{\Delta t_k}\right)_i = \left(\frac{Q_k - Q_{k-1}}{t_k - t_{k-1}}\right)_i \quad i \in [0,365]; k \leq 1 \text{ hour}$$

$$HP2_i = p_{90} \ |(HP2_k)_i|;$$

$$HP2 = \text{median } (HP2_i)$$

Table A.2 List of Indicators of hydrological alteration.

Indicators of Hydrological alteration (Richter et al., 1996)
1 [...] 12 } Magnitude of monthly discharge
13 – Annual minima, 1-day mean
14 – Annual minima, 3-day means
15 – Annual minima, 7- day means
16 – Annual minima, 30-day means
17 – Annual minima, 90-day means
18 – Number of zero-flow days
19 – Base flow index: 7-day minimum flow/mean flow for year
20 – Annual maxima, 1-day mean
21 – Annual maxima, 3-day means
22 – Annual maxima, 7-day means
23 – Annual maxima, 30-day means
24 – Annual maxima, 90-day means
25 – Qp_2: 2 year return period peak discharge
26 – Qp_{10}: 10 year return period peak discharge
27 – Julian date of each annual 1-day maximum
28 – Julian date of each annual 1-day minimum
29 – Number of low pulses within each water year
30 – Number of high pulses within each water year
31 – Rise rates: Mean or median of all positive differences between consecutive daily values
32 – Fall rates: Mean or median of all negative differences between consecutive daily values
33 – Number of hydrologic reversals
Indicators of Hydropeaking (Carolli et al., 2015)
34 - HP1 – Sub-daily flow fluctuations
35 - HP2 – Flow ramping rate

A.3 Assessment of Hydrological alteration

The Range of Variability Approach (RVA) described in Richter et al. (1997) defines alteration for each IHA indicator, so that it can be used as a guide for managing the relevant flow properties. The RVA uses pre-impact data to express the natural range of flow variation. This natural variation is defined dividing the full range of pre-impact data for each IHA (Table A2) into 3 sectors, delineated by the upper and lower quartiles. An expected frequency with which values of the IHA parameters should fall within each of these three sectors is calculated using pre-impact data and is compared with the observed frequency calculated on post-impact data in order to assess the hydrological alteration.

Two widely-used European methods of hydrological assessment use this approach. The IAHRIS (Martínez Santa-María & Fernandez Yuste, 2010) groups the indicators into 3 different categories (*habitual regime*, *flood regime*, *drought regime*), whereas the IARI method (ISPRA, 2009) estimates a single, average index to assess the hydrological status.

For the purposes of REFORM, we adopt the following tiered approach, as it informs the management of single hydrologic indicators, but also allows the user to further summarize indicators into (grouped) ad-hoc indices.

In order to evaluate the alteration of indicator *i* (e.g. Qp_2: 2 year return period peak discharge is referred as no.25 in Table A.2, so *i*=25 in this case), the median value over the post-impact period (e.g. last five years) is calculated, namely $X_{i,k}$. Then, $X_{i,k}$ is compared with the percentiles $XN_{0.25,i}$ e $XN_{0.75,i}$ during the pre-impact period in terms of the distance of $X_{i,k}$ from the nearest percentile.

Successively, the ratio $p_{i,k}$ between the above mentioned distance and the range $XN_{0.25,i}$ - $XN_{0.75,i}$ is calculated (Figure A2). This ratio ($p_{i,k}$) express the alteration of the chosen indicator. Therefore, if $X_{i,k}$ falls inside the inter-quartile range, the $p_{i,k}$ value is recorded equal to 0, which means that there is no alteration.

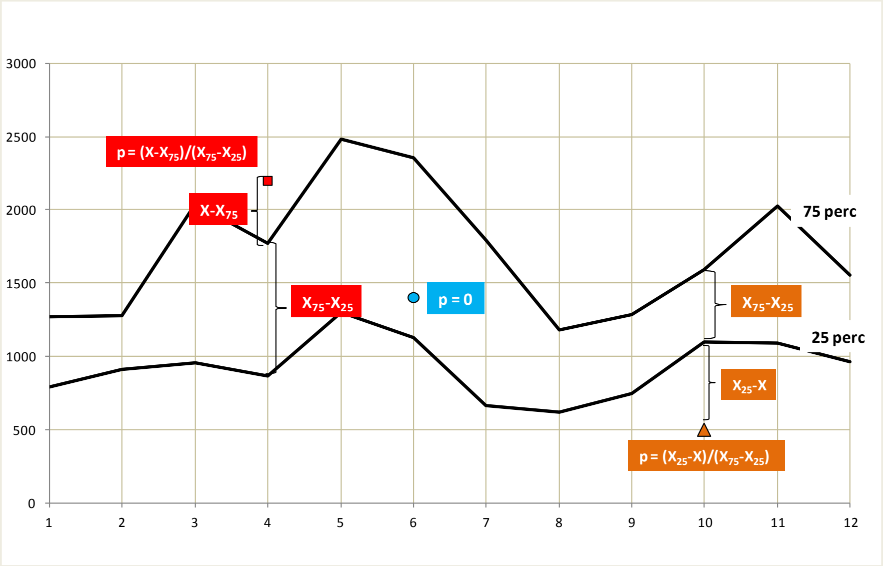

Figure A.2 Calculation procedure.

The following equation summarizes the calculation method:

$$p_{i,k} = \begin{cases} 0 \quad if \quad XN_{0.25,i} \le X_{i,k} \le XN_{0.75,i} \\ \min\left(\left| \dfrac{X_{i,k} - XN_{0.25,i}}{XN_{0.75,i} - XN_{0.25,i}} \right|, \left| \dfrac{X_{i,k} - XN_{0.75,i}}{XN_{0.75,i} - XN_{0.25,i}} \right| \right) \quad if \quad X_{i,k} < XN_{0.25,i} \;\text{ o }\; X_{i,k} > XN_{0.75,i} \end{cases}$$

where:
i is the number of the indicator as in Table A.2;
k refers to the last year of the post impact period;
$X_{i,k}$ is the median value of the post-impact period in the altered conditions;
$XN_{0.25,i}$ is the 25% percentile of indicator *i* in natural conditions (*pre-impact*);
$XN_{0.75,i}$ is the 75% percentile of indicator *i* in natural conditions (*pre-impact*).

A.4 Indicators of Groundwater-Surface water interaction

Spatial scale: *Segment/reach*
Type of data: *Daily river discharge series*

Interaction between groundwater and surface water (GSI) can be defined as the hydraulic, physical-chemical, and biological continuity between groundwater and surface water bodies. Groundwater bodies feed surface water bodies and sustain their flow during dry periods and droughts (eg. Bunke and Gonser, 1997; Dahm et al, 1998).

The river-aquifer system can be considered as a unitary body: thus, groundwater connected rivers can also be seen as the surface expression of the groundwater body to which the river is connected.

The interaction processes between a river and the connected groundwater body depend on climatic, geomorphological, hydrological and hydrogeological factors:

- Geology (stratigraphy, morphology, tectonics) and structural pattern of the aquifer in connection with the river;
- Climate regime and related recharge processes;
- Dynamics of hyporheic zone, which is the groundwater-surface water interface, usually within the alluvial sediments of the river corridor.

The hydrological behaviour of a river, such as its intermittency and perenniality, depends on GSI. Likewise, GSI controls the hydrological response of groundwater stored in the aquifer to precipitation and changing river flows (recharge cycles).

Interaction processes vary in space and time. The spatial scale terminology adopted in the present discussion refers to the REFORM framework (REFORM Deliverable 2.1). Relevant GSI at the various spatial scales of the multi-scale framework are also described in the REFORM Deliverables 2.1 and D6.2 (Part 1).

At the large (regional to catchment) scale, GSI processes affect both regional aquifers and the main rivers that receive groundwater from these aquifers. Interaction between main river networks and groundwater is dynamic and depends on: the geology of groundwater body, the size and morphology of the catchment, and climate.

At the landscape and segment scales, interaction processes also depend on the geological and structural features of the hydrogeological system with which the river is connected, and also the geometry of the hydrogeological boundaries (Castany, 1982).

At the finest sub-reach to geomorphic unit scales, GSI depends on the morphology of the river channel and its floodplain, as well as on the presence and nature of the alluvial sediments and solid geology and the depth and geometry of the hyporheic zone. At this scale, GSI processes impact strongly on the ecological communities of river system, within the channel, riparian zone and hyporheic zones (Dahm et al, 1998).

At the large scale, karstic aquifers show high permeability values, whereas at the fine scale, they show heterogeneous conditions of circulation; they can present very low interaction with the connected river as well as extreme permeability and high water exchange in areas that are most intensely fractured and karstified.

River-aquifer interaction types and hydrological assessment and monitoring methods are summarised in Table A.3 for different spatial units.

Table A.3 Scale dependant GSI and corresponding assessment and monitoring methods.

Scale	GW-SW interaction	Hydrological assessment and monitoring
Catchment/ Landscape unit	Interaction between main hydrostructures (the basal water circulation) and the large rivers that drain them	Water budget analysis
Segment/ Reach unit	Interaction between aquifers and rivers	Streamflow measurements to identify gaining and losing stream segments or reaches Surveys of groundwater flow directions and intensity and water table levels River base flow assessment
Sub-reach/ Geomorphic unit	GSI interaction in the hyporheic riparian zone	Measurements of water table levels (wells, boreholes, piezometers) Detailed survey of groundwater flow field

A.5 GSI monitoring methods

A wide range of methods are used to measure GSI at different spatial scales. They are summarised in Table A.4 and described in detail in the following sections.

Table A.4 Types of analysis of GSI and related spatial scale.

Spatial Scale / GW-SW measures	Water budget analysis	Stream flow measure-ments Hydrograph analysis	Well network measure-ments	Dyes and tracers	Chemical and physical profiling (temperature, pH, Electric Conductivity, etc)	Seepage meters
Catchment/ Landscape Unit	X					
Segment/ Reach		X	X	X	X	
Sub-reach/ Geomorphic unit			X	X	X	X

1. Water budget analysis (Catchment scale)

At catchment scale, GSI processes can be identified by analysis of the water budget. Gauging stations along the river network measure the total volume of water runoff (Total outflow, Figure A.3) and its components (base flow, surface runoff), which can be combined with precipitation measurements to calculate the water going into and out of the catchment and its pathways, including the groundwater component.

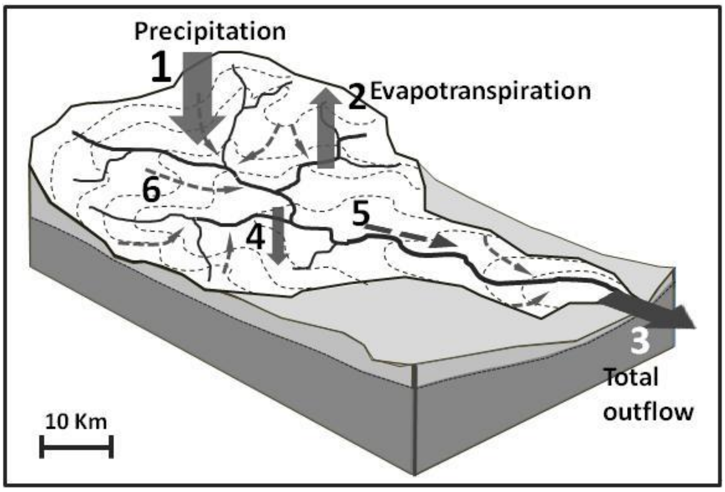

Figure A.3 Catchment scale. The water budget in a hydrogeological closed system: 1) Precipitation (rain, snow); 2) Evapotranspiration; 3) Total outflow (total discharge at the outlet gauging section); 4) Net infiltration (aquifer recharge); 5) surface runoff; 6) groundwater flow.

2. Hydrogeological investigations

The dynamics of GSI can be identified through hydrogeological studies that allow aquifer geometry, groundwater preferential flow lines and their interaction with the surface water bodies to be extracted.

The output of these investigations include hydrogeological contour maps which show, for example, lines of equal hydraulic head across the regional water table and the directions of groundwater flow (Figure A.4). These can be developed for typical (average) conditions and also for specific (e.g. wet and dry) conditions, allowing useful comparisons to be made (WMO, 1029, 1994).

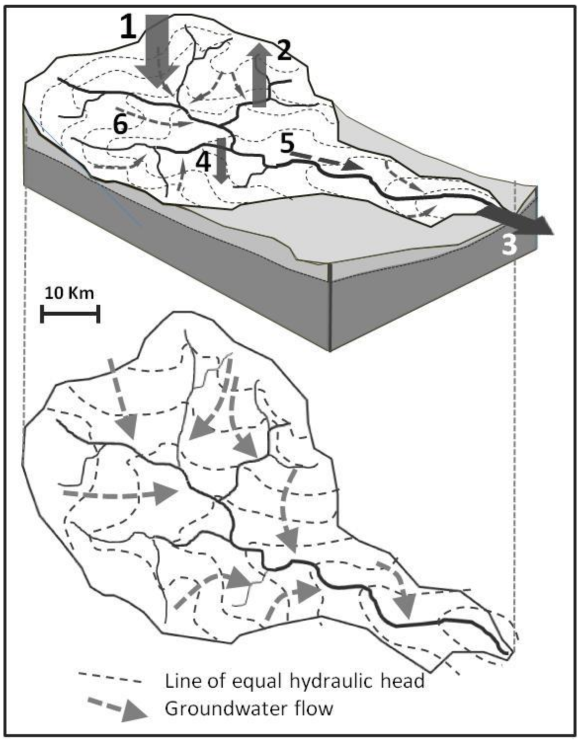

Figure A.4 Hydrogeological analysis to identify interaction at catchment scale between river and groundwater flow.

3. Hydrograph analysis (Baseflow - Surface runoff separation)

As seen in the previous Section, hydrogeological studies allow reconstruction of both groundwater flow direction and river-aquifer interaction.

Hydrograph analysis allows for the calculation and analysis of variations in the contribution of water volumes from different sources or flow pathways (groundwater and surface water) and thus changes in their contribution to the flow regime over time (Huh et al., 2005). As an example, hydrograph analysis allows dry and wet periods of the hydrological year to be distinguished, for example on a monthly basis, and for these periods to be related to variability in the baseflow index (Figure A.5).

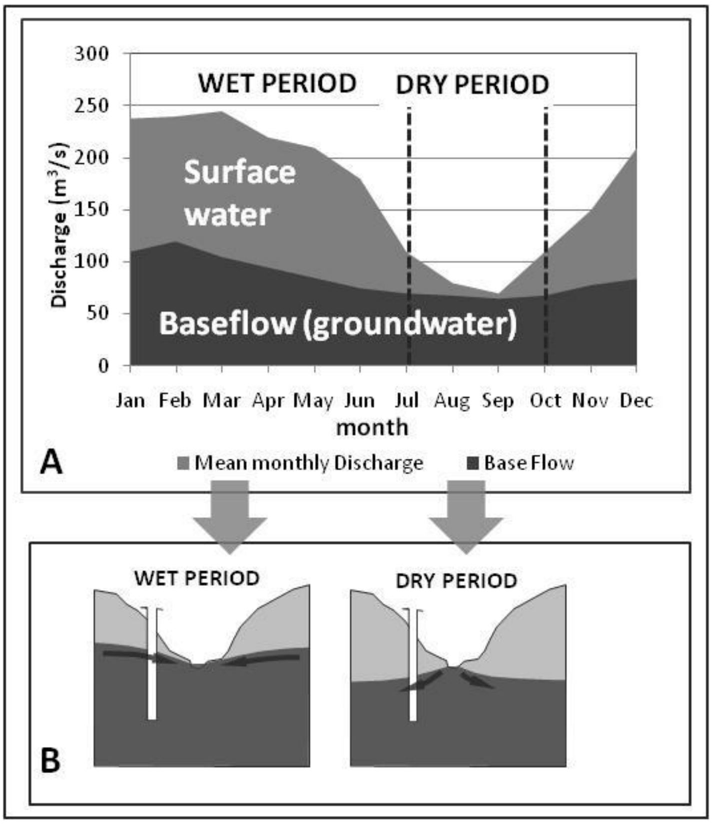

Figure A.5 A) Hydrograph analysis of the contribution of baseflow to the total discharge during wet and dry periods. B) Increase/decrease of streamflow flow along a river reach monitored using well and discharge measurements (from upstream to downstream).

Wet and dry periods can be highlighted in plots of the mean-monthly hydrograph (e.g. Figure A.5 A). These periods represent, respectively, recharge (wet period) and depletion (dry period) conditions of the river-aquifer system.

4. Streamflow measurements

Streamflow measurements indirectly assess the degree of river-aquifer interaction at reach and segment scales: 'gaining-stream' (or 'losing-stream') conditions are shown in Figure A.5 B and Figure A.6. In Figure A.6, streamflow measurements are made at the sites Q1, Q2, Q3 and highlight discharge *increases* (or *decreases*) from upstream to downstream. The hydraulic equipotential lines are reconstructed on the basis of both streamflow measurements and piezometric levels monitored at A, B, C in Figure A.6. They indicate groundwater flow from the riparian zone towards the river or vice versa.

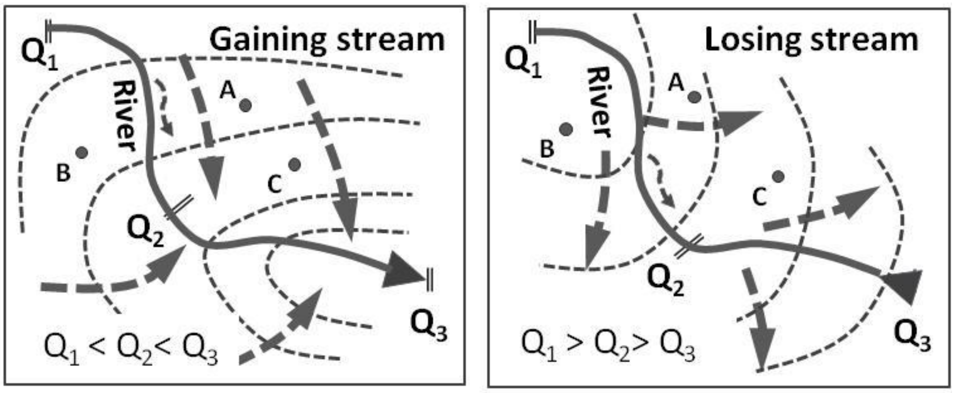

Figure A.6 GSI during base flow conditions (gaining stream: groundwater feeds the streamflow) and dry conditions (losing stream: streamflow feeds the groundwater) . Streamflow measurements along the river reach (Q_1, Q_2, Q_3, from upstream to downstream) allow the flow direction between river and aquifer and the amount of water exchange between the two water bodies to be calculated.

The hydrological indicator, discharge change per unit-length of river (ΔQ/Km) may be positive or negative depending on the type of water exchange. Its determination requires near-synchronous streamflow measurements to be carried out at least seasonally in three or four sections (from upstream to downstream) along the river reach. echniques for streamflow measurement are detailed in manuals such as WMO guidelines no. 1044 (WMO, 2010).

A further hydrological indicator of river-aquifer exchange is the annual minimum discharge, which provides an estimate of the minimum baseflow contribution to the river. This indicator is derived from river flow time series recorded at gauging stations (Gustard et al., 1992), but where there are no such data, it is possible to estimate the indicator by making purpose-specific streamflow measurements during drought periods.

5. Well network measurements

Water table measurements allow the geometry of the piezometric surface of the aquifer and its interaction with the river to be estimated. River-aquifer interactions can be monitored by means of hydraulic head measurements within the fluvial corridor, particularly in the riparian zone (Figure A.7).

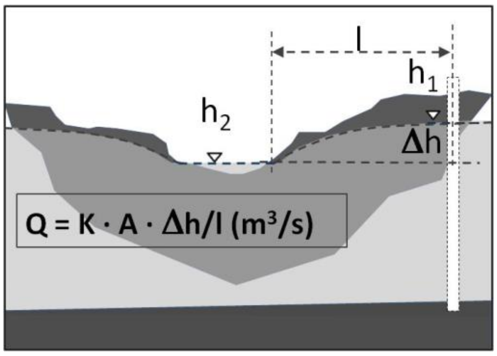

Figure A.7 Hydraulic head measurement through a well.

These monitoring programs are usually carried out on wells, piezometers and micro-piezometers located in the floodplain near the river.

6. Chemical-physical profiling

At sub-reach to geomorphic unit scale, the focus is on processes that take place in the hyporheic zone (Environment Agency, 2005; 2009), namely the transition zone between surface water in the river and the saturated zone within the substrate. The interaction can be described using several methods, including seepage meter measurements, point measurements using dyes and tracers (Harvey et al , 1996; 1993), and thermal or other chemical-physical (pH, conductivity, TDS) profiles (e.g. Voytek et al , 2013).

The physical-chemical characteristics of groundwater (temperature, conductivity, pH, etc.) differ from those of surface water, so the values observed within the river water can be used to distinguish between surface water and groundwater components.

Water temperature profiles taken across river cross sections and along river reaches, can support identification and mapping of groundwater filtration areas into the river channel through the hyporheic zone (Constantz, 2003). Similarly, profiles of electrical conductivity and/or pH values can provide an indication of groundwater seepage areas.

7. Dyes and tracers

The use of natural and artificial tracers allows groundwater flow lines and the timing of underground circulation to be quantified at the fine-local scale (eg. Sub-reach or geomorphic unit). Like the chemical and physical analysis, tracer measurements are taken as point surveys, and give information about local areas at a particular point in time.

A.6 Hydrological indicators and GSI monitoring

Quantitative monitoring of river-aquifer interaction is based on a set of key hydrological parameters (rainfall, discharge, water levels, well and piezometric levels, air temperatures). Starting from these data, hydrological key indicators of GSI can be calculated. Table A.5 shows the key indicators that have been used for assessment and monitoring programs of GSI exchange (from Gustard et. al. 1992; WMO n.1029, 1994).

Table A.5 Synthesis of Indicators of Groundwater – surface water interaction (modified after Gustard et. al., 1992 and WMO n.1029, 1994).

Monitoring techniques	GSI indicator	Unit	Description	Data required
Streamflow measurements	Streamflow	m^3/s	Flow data and arithmetic mean of the flow data series	Daily (or monthly) flows
Hydrograph analysis	Baseflow	m^3/s	Groundwater contribution to the total flow	Daily flows
Hydrograph analysis	Baseflow index	%	Baseflow as a proportion of the total discharge of a river	Daily flows
Hydrograph analysis	Coefficient of variation in annual mean flow	%	Standard deviation of annual mean flow divided by mean flow	Long term data flow
Well networks	Groundwater level	(m)	Variation of hydraulic head within an aquifer	Hydraulic head data, observation wells, bore holes or hand-dug wells
Thermal and physico-chemical profiling	Physico-chemical parameters Temperature, El. Conductivity, pH	°C; µS/cm	Variation in physico-chemical parameters along a river section; thermal and water conductivity variations	Physico-chemical data
Seepage meters	Water flow across bed interface	m^3/s	Direct measure by seepage meters of water flow across the hyporheic zone	Seepage data

A.7 References

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ANNEX B Morphological monitoring indicators

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Introduction

This chapter reviews indicators, evaluation tools, and analyses which are suitable for monitoring morphological conditions. Monitoring is the repeated measurement of parameters and/or a periodic evaluation by some assessment tool to verify whether some change (deterioration or enhancement) of morphological conditions is occurring compared to some initial condition. The review stems from the outputs of REFORM Deliverable D2.1 (Gurnell et al., 2014), but provides more detail on monitoring indicators, evaluation procedures and tools. The types of monitoring according to the Water Framework Directive (WFD) are discussed, and evaluation of potential impacts of new interventions (including restoration actions) is also considered.

B.1 Indicators for morphological characterization

The information assembled during the characterisation phase supports a list of morphological indicators of current and past condition of a catchment and its spatial units. These key indicators, which are summarised in Table B.1, provide an overview of current and past morphological functioning of the catchment and its spatial units.

Table B.1 List of indicators of current and past condition according to the relevant spatial scale, the key processes and criteria that they represent and the human pressures that influence them (from Gurnell et al., 2014).

Spatial Unit	Key Process	Assessed Criteria	Indicators	Alteration Pressures
Catchment	Water Yield	Catchment area	Drainage area (km^2)	Water transfers
		Runoff ratio (coefficient)	Water yield (mm)	De/Afforestation
		Geology	Annual runoff ratio (coefficient)	Agriculture / grazing abandonment
		Land cover	Geology (WFD types)	Major land cover change (e.g. urbanization)
			% siliceous, % calcareous	
			% organic, % mixed /other	
			Land cover (CORINE level 1)	
			% artificial surfaces	
			% agricultural areas	
			% forest and semi-natural areas	
			% wetlands	
LANDSCAPE UNIT	Water Production	Rapid runoff production (low infiltration areas, potential saturated areas)	% area of exposed aquifers	Changes in groundwater exploitation / abstraction
			% area of permeability classes	
			% glaciers and perpetual snow	Changes in land cover / use
			% large surface water bodies	Changes in ice / snow storage
			Land cover (CORINE level 2)	
		Delayed runoff production (high infiltration areas, deep drainage areas)	% area of rapid runoff production (paved or compacted area, urban fabric, industrial, commercial, transport units, open spaces with little or no vegetation)	
			% area of intermediate runoff production (arable land, perm. crops, pastures, shrub and/or herbaceous vegetation)	
			% area of delayed runoff production (forests, wetlands)	

Spatial Unit	Key Process	Assessed Criteria	Indicators	Alteration Pressures
Landscape unit (ctd.)	Sediment production	Fine sediment production	Soil erosion rate (t ha^{-1} y^{-1})	Changes in land cover / use De/Afforestation
		Coarse sediment production	% area with potential sources of coarse Sediment	Intensification of use of agricultural soils Changes in soil conservation practices, buffer strips, natural barriers to soil movement Torrent control
Segment	Water flow	River flow regime^{1*}	Flow regime type^{1*}	Dams, flow regulation, water transfers, hydropower development
			Average annual flow (m^{3} s^{-1}) ^{1*}	
			Average monthly flow (m^{3} s^{-1}, seasonal pattern) ^{1*}	Groundwater exploitation
			Baseflow index (BFI)	
			Morphologically meaningful discharges (Qp$_{median}$, Qp$_{2}$, Qp$_{10}$, m^{3} s^{-1}) ^{1*}	
			Extremes: median, LQ, UQ of 1- and 30- day maximum and minimum flows (m^{3} s^{-1} and month of most frequent occurrence) ^{1*}	
			Hydropeak frequency (number / year) ^{1*}	
	Sediment flow	Sediment supplied to the channel	Eroded soil delivered to channel	Dams, flow regulation
			Land surface instabilities conn. to channel	Major changes in land cover / use
		Sediment transport and storage^{2*}	Measured / estimated suspended sediment load (t y^{-1}) ^{2*}	Removal of riparian vegetation
			Measured / estimated bedload (t y^{-1}) ^{2*}	
			Sediment budget (+ve / -ve channel sediment storage) ^{2*}	
			Number of high channel blocking structures	
			Number of medium channel blocking structs.	
			Number of high spanning/crossing structures	
			Number of medium spanning/crossing structs.	

Spatial Unit	Key Process	Assessed Criteria	Indicators	Alteration Pressures
Segment (ctd.)	River morphology adjustments	Valley controls on channel dynamics	Average valley gradient (m.m^{-1}) Valley confinement River confinement (alluvial plain width / bankfull river width)	Effective valley width can be reduced by human activities but these lateral constraints are assessed at the reach scale
		Riparian corridor features	Average riparian corridor width Proportion of riparian corridor under functioning riparian vegetation Riparian corridor continuity Riparian corridor vegetation cover / structure	Dams, flow regulation Groundwater abstraction Channelization, dredging / gravel mining Floodplain occupation Riparian forest exploitation / management
	Wood Production	Potential wood Delivery	% active channel edge bordered by living / dead trees	Flow regulation / groundwater abstraction Dams, weirs and other blocking structures Channelization, bank reinforcement / protection Beavers Wood removal
Reach	Flooding	Flood area	% floodplain accessible by floodwater	Flow regulation / groundwater abstraction Channelization, embanking Channel incision / aggradation
	Channel self-maintenance / reshaping	Flow energy	Specific stream power (at current mean bankfull width and morphologically meaningful discharge).	Dams, flow regulation Channelization (gradient changes, blocking structures, reinforcement)
		Sediment size	Bed sediment size (D_{50}, dominant size) Bank sediment size (D_{50}, dominant size)	Sediment dredging / mining Vegetation encroachment
		Channel dimensions, type and features	Channel gradient Bankfull channel width Average bankfull channel depth Bankfull channel width:depth ratio Bankfull sinuosity index	Accelerated soil erosion, torrent control

Spatial Unit	Key Process	Assessed Criteria	Indicators	Alteration Pressures
Reach (ctd.)	Channel self-maintenance / reshaping (ctd.)		Braiding index	
			Anabranching index	
			River type	
		Channel dimensions, type and features (ctd.)	Presence of channel and floodplain	
			Geomorphic features / units typical of river type	
			Bars, benches, islands (% area of bankfull channel	
	Channel Change / Adjustments	Lateral migration, planform change	Eroding banks (% active channel bank length)	Flow regulation / groundwater abstraction Bed incision Embanking, revetments Floodplain land occupation Vegetation encroachment
			Laterally aggrading banks (% active channel bank length)	
			Retention of in-channel sediment (% area of bankfull channel)	
			Lateral channel migration rate (m y^{-1})	
			Changes in (i) sinuosity index, (ii) braiding index, (iii) anabranching index	
		Narrowing / widening	Changes in active channel (i) width, (ii) depth, (iii) width:depth ratio	Dams, flow regulation Groundwater abstraction
		Bed Incision / aggradation	Presence of geomorphic features / units indicative of (i) narrowing (ii) widening	Channelization Dredging and gravel extraction (sediment deficit) Accelerated soil erosion (sediment surplus) Urbanization
			Presence of geomorphic features / units indicative of (i) bed incision, (ii) aggradation	
			Changes in bed sediment structure indicating (i) incision, (ii) aggradation	
		Vegetation encroachment	Aquatic / riparian encroachment	

Spatial Unit	Key Process	Assessed Criteria	Indicators	Alteration Pressures
Reach (ctd.)	Channel adjustments (ctd.)	Constraints on channel adjustment	Width of erodible corridor	
			Proportion of potentially erodible channel margin	
			Proportion of river bed that is artificially reinforced	
			Number of high, medium, low blocking or spanning/crossing structures	
	Vegetation succession	Aquatic vegetation	Aquatic plant (i) extent, (ii) patchiness, (iii) species / morphotypes	Flow regulation Groundwater abstraction Channelization Riparian corridor occupation / management Accelerated soil erosion and delivery Invasive species
			Presence of aquatic-plant-dependent Geomorphic units / features	
		Riparian vegetation	Proportion of riparian corridor under mainly mature trees, shrubs, shorter vegetation and bare (recruitment sites)	
			(i) Lateral gradient and (ii) patchiness in riparian vegetation cover classes	
			Dominant riparian tree species	
			Presence / abundance of large wood	
			Presence of wood- or riparian tree-dependent geomorphic units / Features	
	Wood delivery	Large wood and organic debris	Abundance of (i) isolated wood pieces, (ii) in-channel wood accumulations (iii) channel-blocking jams, (iv) wood in the riparian corridor	Vegetation and wood management Dams, flow regulation, flood control Beaver control

[1*] Flow properties are estimated at the segment level to maximise the likelihood of having suitable flow gauging station records, but could also be estimated at the reach level if suitable flow series are available.

[2*] Sediment transport is estimated at the segment scale to link with discharge measurements. However, the measurements or estimates are equally applicable at the reach scale where good information may be available on bed material particle size, local channel gradient and width to support modelling.

B.2 Indicators for morphological monitoring

Starting from the large set of indicators for morphological characterization (Table B.1), a sub-set of potential indicators for monitoring morphological conditions is summarised in Table B.2. The first column reports the main hydromorphological components according to the WFD (continuity, morphology, substrate) to make a more direct link with the requirements of the directive.

Table B.2 Summary of morphological indicators for monitoring hydromorphological conditions.

Components	Key processes	Morphology	Artificiality
Longitudinal continuity	Water flow	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)
	Wood delivery		Alteration of wood delivery from upstream and wood transport (dams, check dams, bridges)
Lateral continuity	Flooding	Width and longitudinal continuity 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	Proportion of protected banks
		Eroding banks	
		Laterally aggrading banks	
		Width and longitudinal continuity of an erodible corridor	
Pattern	Self-maintenance / channel adjustments	Sinuosity index, Braiding index, Anabranching index, River type	Artificial changes of river course (meander cutting, channelization, etc.), bank protections, dams, check dams, weirs
		Presence, variability and extent of instream geomorphic units	
		Presence, variability and extent of geomorphic features in the alluvial plain (including wood)	
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	

Table B.2 (continued).

Components	Key processes	Morphology	Artificiality
Longitudinal profile/Cross-section (ctd.)	Self-maintenance / channel adjustments	Width : depth ratio	
		Variability of cross section	
Bed substrate (including vertical connectivity)	Self-maintenance / channel adjustments	Bed sediment size	Structures or interventions altering bed substrate (revetments, ramps, sills, sediment removal)
		Bed armouring	
		Clogging	
			Wood removal

Indicators listed in Table B.2 concerning morphological elements and parameters (morphology), and indicators concerning artificial elements (artificiality) are illustrated in the next two sections.

B2.1 Indicators of morphology

In Table B.3, a summary of the main indicators related to natural morphological processes and forms is reported, providing some general information on the assessment method and the range of application for each indicator.

Table B.3 Summary of indicators of morphology.

Indicator	Assessment method	Range of application
Longitudinal continuity		
1. Channel-forming discharge	Field measurement of maximum annual peak stage at a gauging station	All rivers; more significant for single-thread alluvial rivers
2. Suspended sediment load	Field measurement	All rivers
3. Bedload	Field measurement	All rivers
Lateral continuity		
4. Width and longitudinal continuity of a modern floodplain	Remote sensing, field survey	Partly confined - unconfined rivers
5. Bank sediment size	Field measurement	Rivers with alluvial banks
6. Eroding banks	Remote sensing, field survey	Partly confined - unconfined rivers
7. Laterally aggrading banks	Remote sensing, field survey	Partly confined - unconfined rivers
8. Width and longitudinal continuity of an erodible corridor	Remote sensing	Partly confined - unconfined rivers
Pattern		
9. Sinuosity index	- Remote sensing - Field measurement	- Single-thread large rivers - Single-thread small rivers
10. Braiding index	- Remote sensing - Field measurement	- Multi-thread large rivers - Multi-thread small rivers
11. Anabranching index	- Remote sensing - Field measurement	- Multi-thread large rivers - Multi-thread small rivers
12. River type	- Remote sensing - Field measurement	- Large rivers - Small rivers
13. Presence, variability and extent of instream geomorphic units	Remote sensing, field survey	All rivers
14. Presence, variability and extent of geomorphic features in the alluvial plain	Remote sensing, field survey	Partly confined – unconfined rivers

Table B.3 (continued).

Indicator	Assessment method	Range of application
Longitudinal profile / cross section		
15. Bed elevation	- Total station/GPS survey - Bathymetric survey - DEMs	- Wadable rivers - Non wadable rivers
16. Channel gradient or bed slope		
17. Bankfull channel width	- Remote sensing - Field survey	- Large rivers - Small rivers
18. Bankfull channel depth	- Total station/GPS survey - Bathymetric survey	- Wadable rivers - Non wadable rivers
19. Width : depth ratio		
20. Specific stream power	See 1, 16, and 18	
21. Variability of cross section	- Field assessment/remote sensing	All rivers
Bed substrate		
22. Bed sediment size	Field measurement	All rivers except bedrock
23. Bed armouring		Not applied to bedrock, boulder-bed and sand-bed rivers
24. Clogging		Not applied to bedrock and sand-bed rivers

In Table B.3, 'large rivers' generally indicate channels of relatively large size, i.e. with a channel width>30 m, whereas 'small rivers' indicate channels with a size ranging from intermediate to small (channel width≤30 m). However, a fixed threshold in stream size should be avoided, but the operator should evaluate whether the resolution of available images is sufficient to carry out a remote sensing analysis or field survey is necessary.

A monitoring protocol for each relevant indicator is reported below. The monitoring protocol provides definitions and then summarises various aspects, including the morphological and ecological relevance of the parameter, the monitoring (assessment / measurement) methods, ranges of application, spatial scale at which the monitoring is applied, replication or frequency of measurements, difficulties.

Longitudinal continuity

Indicators of longitudinal continuity concern the driving variables of channel morphology, i.e. water and sediment flow. These indicators provide invaluable information on sediment transport, but their periodic measurement is difficult to achieve. However, when available they would be extremely useful and could be used when some specific problem related to water and/or sediment discharge needs to be investigated. Given the complexity of the topic, some general considerations are reported for the next three indicators, but specialist texts should be consulted for more detail.

1. Channel-forming discharge

Definition

Different morphologically meaningful discharges are used to define the range of potentially channel-forming discharges (Qp_{median}, Qp_{2}, Qp_{10}).

Relevance

Alteration of channel-forming discharge may have important direct effects on channel morphology and indirect effects on physical habitats.

Monitoring methods

Monitoring channel-forming discharge is based on monitoring and updating the data series of annual peak discharge, which is part of the Annex 2A Hydrological monitoring indicators.

Ranges of application

Potentially all rivers.

Spatial scale

Segment.

Frequency of measurement

Hourly or daily discharge.

2. Suspended sediment load

Definition

Suspended sediment that is being transported within a river channel by the flow (often past a particular location within a particular time period).

Relevance

Alteration of suspended sediment load may have important effects on the development of particular geomorphic units and therefore on the character and diversity of physical habitats. An increase in suspended sediment load may cause alteration of the bed structure (i.e. clogging), which may have direct effects on biological communities.

Monitoring methods

Sediment transport is not monitored as commonly as water discharge, and most European rivers have very limited or no sediment monitoring records. Suspended sediment is more commonly monitored than bedload transport, as it is an aspect of water quality that is typically measured by water companies and national environmental agencies. When a gauging station exists and long-term monitoring data are available, continuation of suspended sediment load measurements should be maintained if at all possible. For more details on suspended load sampling and monitoring see Hicks and Gomez (2003).

Ranges of application

Potentially all rivers.

Spatial scale

Segment.

Frequency of measurement

Hourly or daily measurements.

3. Bed load

Definition

Sediment that is being transported on the bed of a river channel by the flow (often past a particlar location within a particular time period).

Relevance

Compared to suspended sediment load, alteration of bed load may have more significant effects on channel morphology, and therefore on the character and diversity of physical habitats.

Monitoring methods

Bedload transport is rarely measured along European rivers, and monitoring stations are usually located only in areas where bedload poses a very significant river management problem. As for suspended load, when a gauging station exists and long-term data are available, bedload monitoring activity should be maintained if at all possible. For more details on suspended load sampling see Hicks and Gomez (2003) and Piégay et al. (2008).

Ranges of application

Potentially all rivers.

Spatial scale

Segment.

Frequency of measurement

Hourly or daily measurements.

Lateral continuity

4. Width and longitudinal continuity of a modern floodplain

Definition

The modern floodplain represents the portion of the overall floodplain that is readily accessible by floodwater. It is therefore an indicator of the lateral continuity of flows. A river in dynamic equilibrium builds a modern floodplain (i.e., a surface created under current conditions) that is inundated during discharges just exceeding channel-forming flows (typical return interval of 1÷3 years). The presence and extent of a modern floodplain are quantified in terms of its mean width and longitudinal continuity along the reach.

Relevance

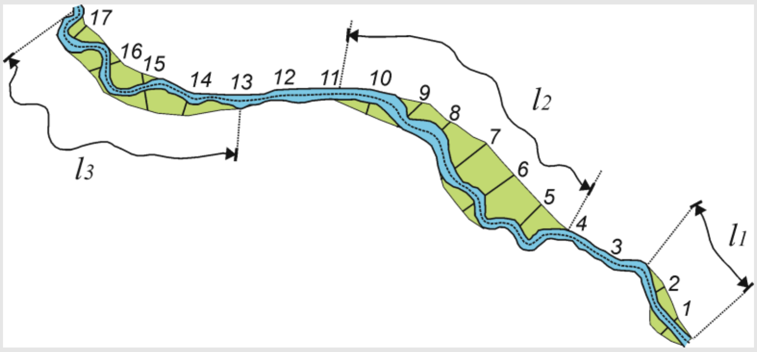
The presence of a modern floodplain that is frequently flooded promotes several important morphological, hydrological and ecological functions (attenuation of flood peak discharges, energy dissipation, fine sediment deposition, groundwater recharge, flood pulse, turnover of riparian habitats, etc.). Channel adjustments (specifically bed incision) or artificial structures (levees) can alter this characteristic form and disconnect the floodplain (which becomes a terrace) from channel processes.

Monitoring methods

Remote sensing–GIS: measurement of width and longitudinal continuity (quantitative);
Field survey: identification/checking of modern floodplain (qualitative).

Measurement procedure

1. Identification and delimitation of the modern floodplain by remote sensing/GIS and field survey.
2. After the modern floodplain has been delimited, two parameters are used to quantify the presence and extension of this surface: 'Width' and 'Longitudinal continuity'.
3. The "Width of the modern floodplain" (*Wfp*) (in m) is intended as the overall width, i.e. the sum along the two sides of the channel including the islands, and is measured by two possible ways: (1) repeated measures along a series of transects to obtain the mean value along the reach (Figure B.1); (2) dividing the floodplain area by the reach length.
4. "Longitudinal continuity of the modern floodplain" (*Lcfp*) is expressed as the portion of the reach (in % of reach length) where a modern floodplain exists on at least one side of the river (Figure B.1).



$$Lc_{fp}= \frac{l1+l2+l3}{l} \ (\%)$$

Figure B.1 Measurement of the Width (W_{fp}) and Longitudinal continuity (Lc_{fp}) of the modern floodplain. The green area represents the modern floodplain along the reach. The width is obtained by the average of the cross sectional width measurements along the transects from 1 to 17. The longitudinal continuity is expressed as the percentage of the total reach length (l) where a floodplain exists on one or both river sides (i.e. l1, l2, l3).

Ranges of application

This indicator is applied to partly confined and unconfined rivers.

Spatial scale

Reach.

Frequency of measurement

Possible changes in the presence and extent of a modern floodplain can be related to lateral mobility of the channel (bank retreat or advance), incision, construction or removal of artificial levees, restoration interventions aimed at floodplain re-creation.

Repeat measurements are only necessary when changes attributable to some of these possible causes occur, otherwise (e.g. in the case of a stable or urbanized river), it is not necessary to replicate the measurement.

5. Bank sediment size

Definition

This indicator evaluates the typical size of the sediment composing the streambanks.

Relevance

The calibre of sediment at the channel boundaries (bed and banks) is another fundamental control on river channel morphodynamics. Bank sediment size influences the erodibility of streambanks, and the size of material that can be delivered to sediment transport by lateral erosion. It also provides information on some characteristics of riparian habitats.

Monitoring methods

Field measurement: identification of bank sediment size needs a field assessment and preferably field sampling.

Measurement procedure

1. The characteristic calibre of bank sediment needs, at a minimum, to be distinguished to the qualitative level of bedrock, boulders, cobbles, gravel, sand and silt, clay. This information is usually collected in the field, although bedrock- or boulder-dominated reaches are sometimes distinguishable on aerial imagery. Some variability of bank typologies (cohesive, non cohesive, composite, etc.) and consequently of the sediment size can be observed at the reach scale, in such case the predominant sizes should be noted. Where there is a mix of two dominant sediment sizes, a combined descriptor can be used such as boulder-cobble.
2. Given that bank sediment size is crucial to characterizing channel morphodynamics, collection of some representative sediment samples from the field is strongly recommended. The following parameters can be extracted if a complete particle size distribution is estimated from such samples: (1) Median particle size / D_{50}; (2) Sorting coefficient (width of the particle size distribution); (3) Skewness (asymmetry of the distribution); (4) Kurtosis (peakedness of the distribution).

Ranges of application

All rivers except bedrock channels.

Spatial scale

The characteristic calibre of bank sediment at a qualitative level is collected at reach scale. Bank sediment sampling is conducted at representative sites.

Frequency of measurement

Changes in bank sediment size normally occur at a longer time scale compared to other indicators and so repeat measurements are not usually necessary and a single observation (or periodic measurements with a low frequency) of this indicator can be conveniently used to integrate the characterization of river conditions.

6. Eroding banks

Definition

This indicator evaluates the length of retreating banks along the reach and the mean rate of bank retreat.

Relevance

Bank erosion is often perceived as a negative process. However, eroding streambanks are also a natural feature of channels that are dynamically stable and represent a key process contributing to sediment supply as well as to the development of riparian habitats. Some bank erosion is increasingly recognised to be a positive attribute for aquatic and riparian ecosystems (Florsheim et al., 2008). The rate of lateral changes is also very relevant: high rates of erosion can be related to channel instability, and may be responsible of excessive sediment supply, whereas low rates can be associated to excessive stability.

Monitoring methods

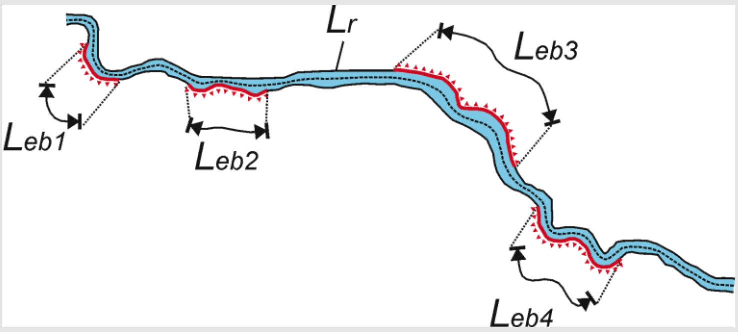
Remote sensing and/or field survey: identification of the presence of eroding banks (qualitative), where eroding banks are normally characterized by natural (unreinforced) unvegetated or scarcely vegetated, vertical, vertical/undercut, and vertical with toe bank profiles.

Remote sensing–GIS: length of eroding banks and rate of retreat (quantitative).

Measurement procedure

1. Identification of eroding banks along the reach by remote sensing and/or field inspections.
2. Two parameters are used to quantify eroding banks: "Length of eroding banks" and "Rate of bank retreat".
3. The "Length of eroding banks" (L_{eb}) (in m and/or % of the sum of the two banks or, equivalently, double the channel reach length) is measured within a GIS as the total length of eroding banks along the reach (Figure B.2).
4. To evaluate the rate of bank retreat, at least two remotely sensed images are compared by GIS analysis spanning a given interval of time. A first step consists of orthorectification and georeferencing of each image, followed by digitising the position of the channel banks.
5. A series of measurements of bank retreat are carried extracted at a regular spatial interval (the same interval used for the measurement of Channel width can be used) within a GIS (Figure B.2).
6. A mean value of bank retreat along the reach is calculated (in the case of stable or advancing banks, bank retreat is assumed equal to zero), and then this is divided by the time in years between the two analyzed images, obtaining a mean "Rate of bank retreat" (R_{br}) (in m/year).

A



$$L_{eb} = \frac{Leb1+Leb2+Leb3+Leb4}{Lr}\ (\%)$$

B

Figure B.2 Measurement of the Length of eroding banks (L_{eb}) (A), and the Rate of bank retreat (R_{br}) (B).

Ranges of application

This indicator is relevant to unconfined and partly confined rivers. In confined channels lateral erosion is prevented by the presence of hillslopes and is normally insignificant.

Spatial scale

Reach.

Frequency of measurement

A periodic assessment of this indicator depends on the availability of new remotely sensed data (aerial photos or satellite images), but an interval of about 6 years is usually feasible.

7. Laterally aggrading banks

Definition

This indicator evaluates the length of the active channel bank showing stabilising (vegetating) marginal bar, floodplain and bench features, and the rate of bank advance.

Relevance

Aggrading banks are common features in a natural channel that is dynamically stable, and are extremely important from an ecological point of view because they are associated to the development of the floodplain and riparian vegetation and habitats.

Monitoring methods

Remote sensing and/or field survey: identification of presence of laterally aggrading banks (qualitative)

Remote sensing–GIS: length of laterally aggrading banks and rate of advance (quantitative)

Measurement procedure

1. Identification of laterally aggrading banks along the reach by remote sensing and/or field inspections.
2. Two parameters are used to quantify laterally aggrading banks: "Length of laterally aggrading banks" and "Rate of bank advance".
3. The "Length of laterally aggrading banks" (L_{lab}) (in m and/or % of the sum of the two banks or, equivalently, of the double of the channel reach length) is measured within a GIS as the total length of laterally aggrading banks along the reach (similarly to the eroding banks).
4. Similarly to the rate of bank retreat, at least two remotely sensed images are compared by GIS analysis spanning a given interval of time to evaluate the rate of bank advance. A first step consists of orthorectification and georeferencing of each image, followed by digitising the the position of the channel banks.
5. A series of measurements of bank advance along the reach are carried out at a regular spatial interval (the same interval used for the measurement of Channel width can be used) within a GIS.
6. A mean value of bank advance along the reach is calculated (in the case of stable or retreating banks, bank advance is assumed equal to zero), and then this is divided by the difference in years between the two analyzed images, obtaining a mean "Rate of bank advance" (R_{ba}) (in m/year).

Ranges of application

This indicator is most relevant in the case of alluvial, unconfined and partly confined rivers, but can be also significant in confined channels.

Spatial scale

Reach.

Frequency of measurement

A periodic assessment of this indicator is related to the availability of new remotely sensed data (aerial photos or satellite images), but an interval of about 6 years is usually feasible.

8. Width and longitudinal continuity of a potentially erodible corridor

Definition

This indicator evaluates the width and longitudinal length of a potentially erodible corridor (*EC*), i.e., an area not protected by structures (e.g., bank protections, levees) or infrastructure (e.g., houses, roads) and thus could be potentially eroded by lateral channel migration. This surface can also include recent, erodible terraces which are external to the modern floodplain (or where a modern floodplain is absent).

Relevance

The presence and a sufficient extent of potentially erodible corridor is a positive attribute, allowing natural lateral mobility and providing a supply of sediment.

Monitoring methods

Remote sensing–GIS: measurement of width and longitudinal length of the potentially *EC* (quantitative).

Measurement procedure

1. As a first approximation, the *EC* is first delimited by remote sensing – GIS, as the area not protected by structures (e.g., bank protections, levees) or infrastructure (e.g., houses, roads), since these latter areas would be definitively protected if bank retreat were to occur.
2. After the *EC* has been delimited, two parameters are used to quantify the presence and extension of this surface: ‘Width’ and ‘Longitudinal continuity’.
3. The “Width of the erodible corridor” (W_{EC}) (in m) is intended as the overall width along both sides of the channel, and is measured in two possible ways: (1) repeated measures along a series of transects to obtain the mean value along the reach (similarly to the width of the modern floodplain in Figure B.1); (2) dividing the area of the ***EC*** by the reach length.
4. “Longitudinal continuity of the erodible corridor” (Lc_{EC}) is expressed as the portion of the reach (in % of reach length) where an *EC* exists on at least one side of the river (similarly to the longitudinal continuity of the modern floodplain in Figure B.1). This measure corresponds to the proportion of channel length with a potentially erodible channel margin on one or both sides.

Ranges of application

This indicator is suitable for unconfined or partly confined rivers.

Spatial scale

Reach.

Frequency of measurement

The extension of an *EC* can occur in relation to lateral mobility of the channel (bank retreat or advance), construction or removal of structures and infrastructures. Only where some of these possible adjustments occur is a new assessment necessary, otherwise (e.g. in the case of a stable or urbanized river) replicate measurements are unnecessary.

Pattern

9. Sinuosity index

Definition

The sinuosity index is the ratio between the distance measured along the (main) channel and the distance measured following the direction of the overall planimetric course of the river. The index generally refers to the bankfull channel. The baseflow sinuosity index can be also of interest, but is more variable, reflecting flow conditions at the moment of the measurement.

Relevance

The sinuosity index is an important parameter when classifying the channel pattern of single-thread rivers, since changes in sinuosity index may reflect variations in the overall channel morphology.

Monitoring methods

Remote sensing–GIS: for rivers of any size (when the planimetric course is visible).
Field measurement: for small rivers when excessive riparian vegetation cover prevents the identification of the planimetric course from remote sensing.

Measurement procedure

Remote sensing – GIS

1. Orthorectification and georeferencing of each image, followed by digitising the

bankfull channel axis or center line, defined as the mid-line between the margins of the bankfull channel.
2. Definition of the 'axis of the overall planimetric course' or 'meander belt axis'. This is the axis of the overall corridor of development of the planimetric pattern or the meanders envelope, as defined by various authors (e.g. Brice, 1964; Malavoi and Bravard, 2010; Alber and Piégay, 2011).
The axis can be a polyline of linear segments, or it can be curvilinear (e.g. Malavoi and Bravard, 2010). In the former case, each linear segment should reflect the changes in direction of the overall course (normally for a length not lower than about 20 times the channel width). Another approach, which is preferable because it minimises subjectivity, defines the meander belt axis as the polyline connecting the inflection points of the channel axis (i.e. the half-meander sinuosity following the terminology of Howard and Hemberger, 1991; see also Alber and Piégay, 2011).
3. Measurement of the channel distance along the channel center and the corresponding distance along the axis of the planimetric course within the upstream and downstream boundaries of the reach.
4. The "Sinuosity index" (Si) is calculated as the ratio of the distance along the bankfull channel axis (or center line) to the distance along the axis of the overall planimetric course.
5. Similarly, the "Baseflow sinuosity index" (Si_{bf}) can be also measured as the ratio of the distance along the baseflow channel axis (defined at the mid-point between the margins of the water-filled channel at typical baseflow conditions) to the distance along the axis of the overall planimetric course.

Field survey
For small streams, the distance along channel the center line is best measured by field topographic survey, while the length distance the axis of the planimetric course can be defined within a GIS, once the channel center line has been visualized.

Ranges of application

The sinuosity index is widely used to classify single-thread rivers, particularly those that are unconfined and partly confined. Its measurement is not very informative in the case of confined rivers, where the planimetric pattern is controlled by the hillslopes, and the distance along the axis of the overall planimetric course coincides with the distance along the channel (resulting in theory to a sinuosity index of 1). In the case of braided rivers, the sinuosity index is generally not meaningful for the classification of planform pattern, but it can be useful to assess possible variations of channel morphology through time (e.g., transitions from braided to single-thread). In the case of anabranching rivers, it can be useful to measure the index for each anabranch channel, and the overall sinuosity index can be calculated as the average of the values of from each channel.

Spatial scale

Reach.

Frequency of measurement

Replication of measurements by remote sensing depends upon the availability of new remotely sensed data (aerial photos or satellite images), but an interval of about 6 years is usually feasible.

10. Braiding index

Definition

The braiding index is defined as the number of active channels separated by bars at baseflow.

Relevance

The braiding index is an important parameter for classifying channel pattern.

Monitoring methods

Remote sensing–GIS: for sufficiently large rivers.
Field measurement: for small streams.

Measurement procedure

Remote sensing – GIS

1. Definition of inter-distance of measurements. Measurements from at least 10 cross-sections are necessary, spaced no more than one braid plain width apart. For a very accurate measurement, a longitudinal interval of 0.25÷1 bankfull widths is recommended (the same inter-distance used for the measurement of other planimetric parameters).
2. For each cross-section, the number of active channels is counted. Only channels that sustain continuous baseflow should be considered. This measurement can be a little subjective, since it is influenced by the flow stage at the time of the image. In order to minimize such errors, images surveyed during extreme situations (such as during or immediately after a high flow event, or during periods of very low flow conditions) should be excluded.
3. The final value of the "Braiding index" (*Bi*) is the average of the measurements along the reach.

Field survey

In the case of small streams, where the resolution of aerial photos is not sufficient to identify baseflow channels, measurements are carried out in the field. In this case, measurements from some representative sub-reaches is usually sufficient.

Ranges of application

For channel classification, measurement is necessary when more than one active channel is widely observed along the reach. The braiding index is typically used to discriminate braided from transitional (wandering) rivers. It is not meaningful in the case of single-thread rivers, where mid-channel bars are absent or negligible. It could be applicable to high energy anabranching rivers, where more active channels may exist and be separated by bars.

Spatial scale

Remote sensing – GIS: reach.
Field survey: representative sub-reach(es) (sites).

Frequency of measurement

Replication of measurements by remote sensing is related to the availability of new remotely sensed data (aerial photos or satellite images), but an interval of about 6 years is usually feasible.

11. Anabranching index

Definition

The anabranching index is defined as the number of active channels at baseflow separated by vegetated islands.

Relevance

The anabranching index is an important parameter for classifying channel pattern.

Monitoring methods

Remote sensing–GIS: for sufficiently large rivers.
Field measurement: for small streams.

Measurement procedure

Remote sensing – GIS

1. Definition of inter-distance of measurements. At least 10 cross-sections spaced no more than the maximum width of the outer wetted channel are necessary. For a very accurate measurement, a longitudinal interval of 0.25÷1 bankfull widths is recommended (the same interval used for the measurement of channel width).
2. For each cross-section, the number of active channels at baseflow separated by vegetated islands is counted. As for the braiding index, channels that sustain continuous flow should be considered, and images surveyed during extreme situations (flood, drought) should be excluded.
3. The final value of the "Anabranching index" (*Ai*) is the average of the measurements along the reach.

Field survey

In case of extremely small streams, where the resolution of aerial photos is not sufficient to identify baseflow channels and islands, the measurement is carried out in the field. In this case, measurements from some representative sub-reaches is usually sufficient.

Ranges of application

The anabranching index is typically used to define anabranching rivers. It is not meaningful in the case of rivers where islands are absent or rare. For channel classification, the measurement is necessary when islands are seen reasonably frequently along the reach.

Spatial scale

Remote sensing – GIS: reach.

Field survey: representative sub-reach(es) (site).

Frequency of measurement

Replication of measurements by remote sensing depends upon the availability of new remotely sensed data (aerial photos or satellite images), but an interval of about 6 years is usually feasible.

12. River type

Definition

This indicator defines the morphological type of the river reach. At a first level ("basic river typology") used for segmentation, the river type is based on valley confinement and morphological planform and therefore on the values of the sinuosity, braiding, and anabranching indices. At a second level ("extended river typology"), other characteristics are taken into account, particularly bed sediment calibre.

Relevance

River type reflects the interactions between driving variables (flow regime and sediment transport) and the boundary conditions characterising a river reach. It is a fundamental feature used for classification and segmentation. Channel types provide a fundamental link between morphological and biological conditions, as they provide information on the characteristic pattern and diversity of physical habitats.

Monitoring methods

Remote sensing–GIS: for sufficiently large rivers.

Field measurement: for small streams. In the "extended classification", a field visit is necessary for identification of sediment calibre (see indicator 22. Bed sediment size).

Measurement procedure

Basic River Typology (BRT)

1. Measurement by remote sensing-GIS or in the field for small streams of sinuosity, braiding, and anabranching indices, when applicable (see indicators 18, 19, 20).
2. Identification of the river type is based on the range of values of these indices and on valley confinement (Table B.4 and Figure B.3).

Table B.4 Basic River Typology (*BRT*) based on Confinement and Planform. *Si*: sinuosity index; *Bi*: braiding index; *Ai*: anabranching index.

Type	Valley Confinement	Threads	Planform	*Si*	*Bi*	*Ai*
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

Type	Valley Confinement	Threads	Planform	*Si*	*Bi*	*Ai*
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

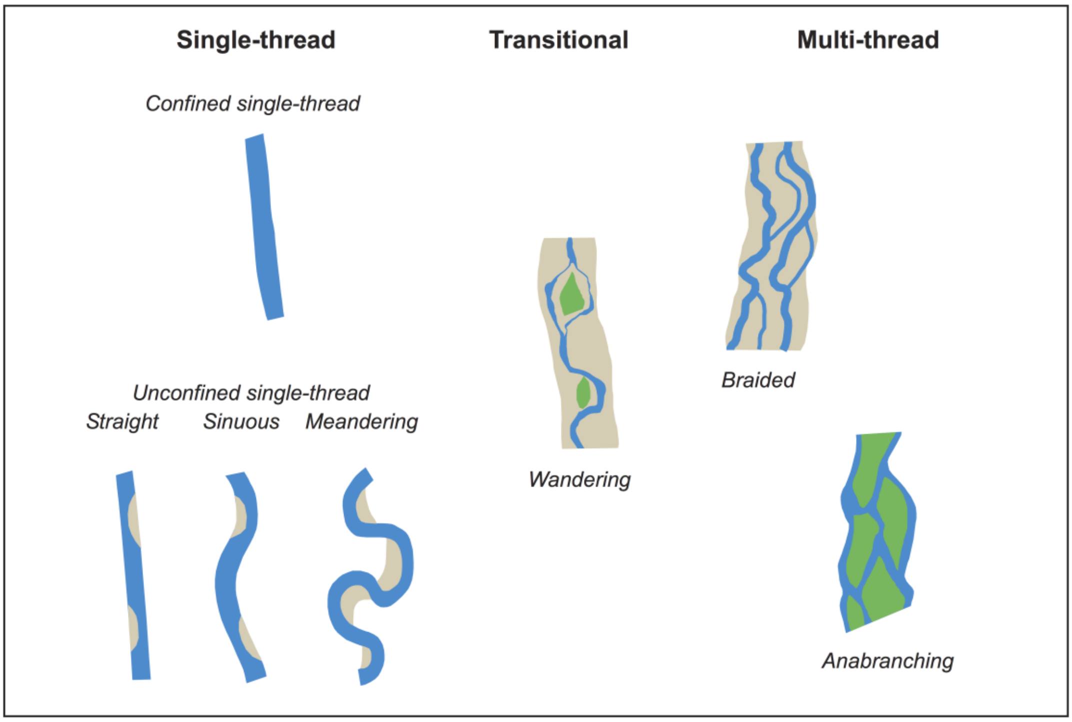


Figure B.3 The seven types of the Basic River Typology (*BRT*).

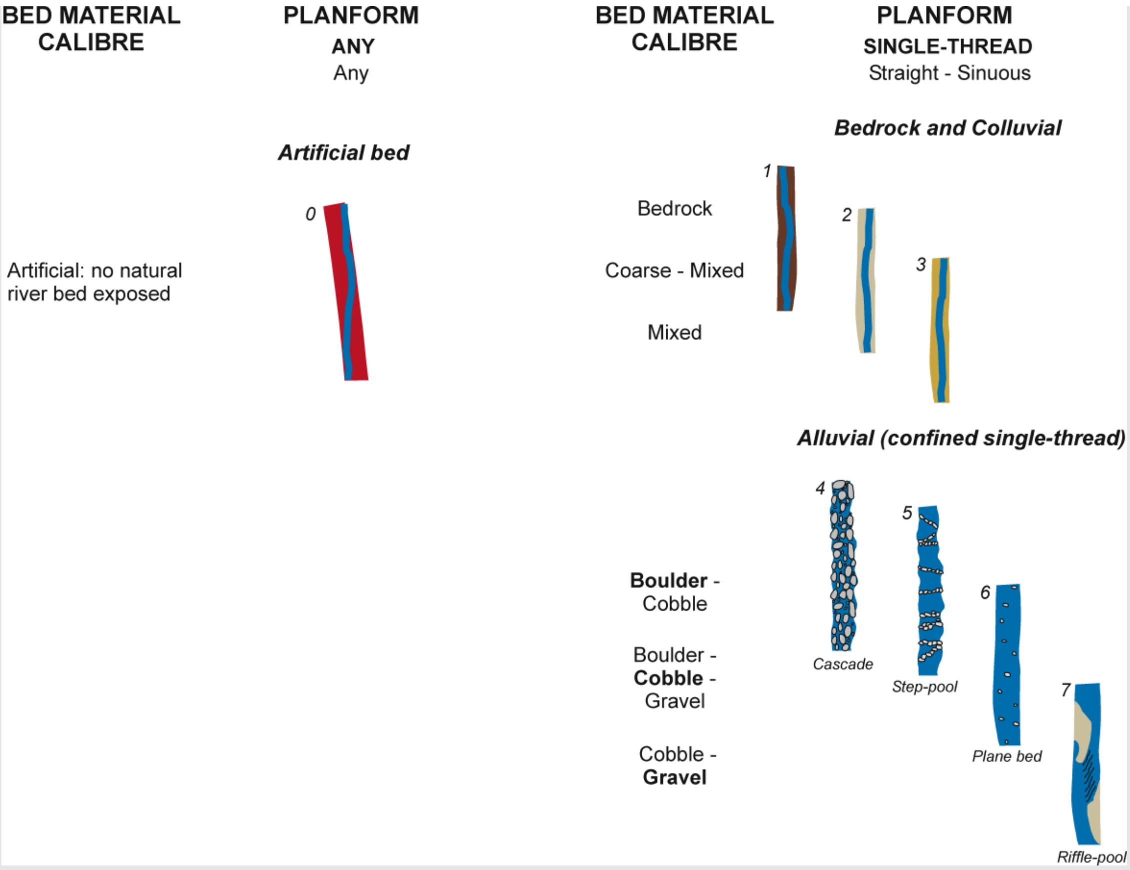


Figure B.4 Extended River Types 0 to 6.

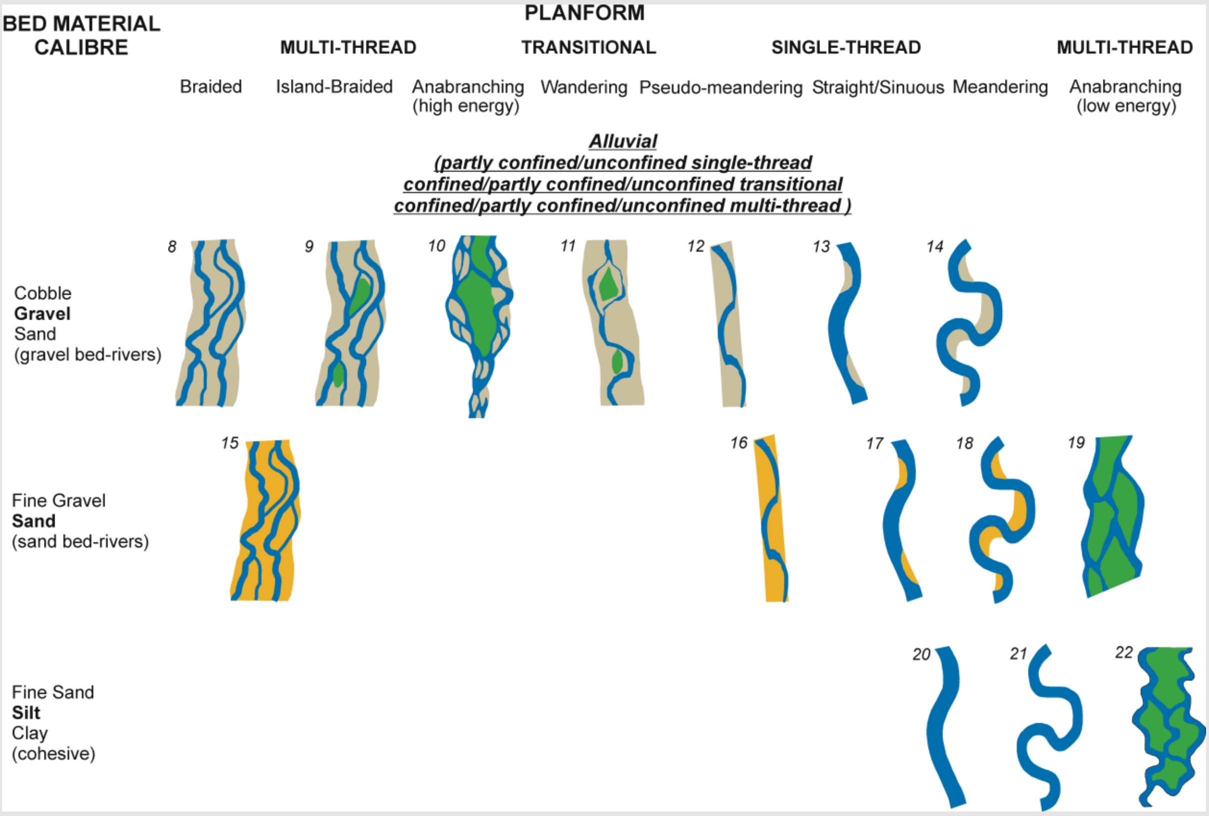


Figure B.5 Extended River Types 7 to 22.

"Extended River Typology (ERT)"
At the second level of the "Extended River Typology", sediment calibre (indicator 22) and geomorphic units (indicator 13) are also considered, obtaining 22 river typologies (Figures B.4 and B.5).

Ranges of application

Classification of river type applies to all rivers.

Spatial scale

Reach.

Frequency of measurement

Temporal changes in channel pattern are monitored by periodically measuring sinuosity, braiding, and anabranching indices and by observation of additional features. Replication of measurements by remote sensing is related to the availability of new remotely sensed data (aerial photos or satellite images), but an interval of about 6 years is usually feasible.

13. Presence, variability and extent of instream geomorphic units

Definition

Geomorphic units are the fluvial landforms that are present in a river reach. Types, variability, and spatial extent of the geomorphic units are fundamental to assessing whether the river is functioning according to its type.

Relevance

Geomorphic units are important for assessing whether a river type is showing natural function and, because they provide different types of physical habitat, they are important indicators of both morphological and biological conditions. Temporal changes in the types of geomorphic unit present as well as their frequency and diversity can be associated with changes in driving variables (flow and sediment discharge), channel adjustments (incision, aggradation), and human alterations.

Monitoring methods

For the classification and survey of geomorphic units, a combination of methods and approaches is used, including: *Remote sensing–GIS mapping; Field assessment.*

Assessment procedure

The *Geomorphic Units survey and classification System* (*GUS* has been specifically developed for this purpose. This methodology is widely illustrated in **Deliverable D6.2 Part 4**.

Ranges of application

Each river type presents a particular set of geomorphic units if it is functioning naturally.

Spatial scale

Remote sensing – GIS analysis can be conducted at reach scale, whereas field survey is normally limited to a representative sub-reach (site).

Frequency of measurement

Replication is desirable on representative sub-reaches, particularly following some pressure or intervention.

14. Presence, variability and extent of geomorphic features in the alluvial plain

Definition

This indicator evaluates the presence, variability and spatial extent of fluvial landforms existing in the alluvial plain.

Relevance

Geomorphic features in the alluvial plain are important for the classification of the floodplain type. They provide a fundamental link between morphological and biological conditions. Temporal changes in the types, variability and frequency of geomorphic units can be associated with changes in controlling factors (climate, flood frequency, etc.) and human alterations.

Monitoring methods

For the classification and survey of geomorphic units, a combination of methods and approaches is used, including: *Remote sensing–GIS mapping; Field assessment.*

Measurement procedure

The *Geomorphic Units survey and classification System* (*GUS*) has been specifically developed for this purpose. This methodology is widely illustrated in **Deliverable D6.2 Part 4**.

Ranges of application

All river types found in unconfined or partly confined reaches.

Spatial scale

Remote sensing – GIS analysis can be conducted at the reach scale, whereas field survey is normally limited to a representative sub-reach (site).

Frequency of measurement

Replication is desirable on representative sub-reaches, particularly following some pressure or intervention.

Longitudinal profile / Cross section

15. Bed elevation

Definition

Bed elevation is usually defined as either the elevation of the deepest point in the channel bed (minimum bed elevation or thalweg) or the mean bed elevation.

Bed elevation can be measured at the scale of a single cross-section or at the reach scale as a longitudinal profile. The term “longitudinal profile” refers to a graphical 2D representation of bed morphology, where bed elevation is plotted against longitudinal distance downstream measured along the channel.

Relevance

Longitudinal surveys provide the necessary data for estimating a number of other channel properties, including the slope of the thalweg, the spacing of bed morphological units (pools, steps, etc.), and breaks in slope in the channel’s long profile. Temporal changes in bed elevation are used to assess trends in bed-level adjustments.

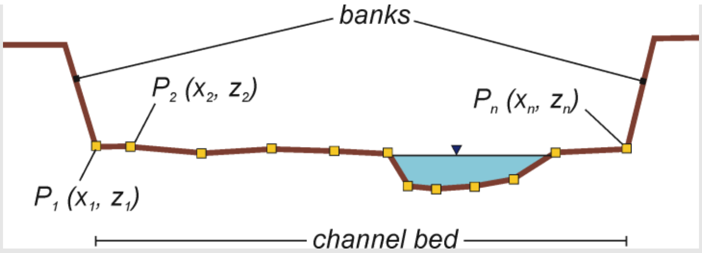
Monitoring methods

Field measurement: total station/GPS survey for wadable rivers; *bathymetric survey* for non-wadable rivers.

Measurement procedure

Bed elevation at a cross-section

1. Depending upon the level of accuracy desired and the site conditions, various techniques can be used for topographic survey of channel cross-profiles (see also “Channel depth” for more details), but the use of a total station or differential GPS are recommended. Where flows are too deep to obtain measurements of bed elevation by these methods, bathymetric surveys by sonar systems or echo-sounding can be used.
2. For a given cross-section, the “Minimum bed elevation” (Z_{min}) (m a.s.l.) is the deepest point of the channel bed. The “Mean bed elevation” (Z_{mean}) (m a.s.l.) can be obtained as the average elevation of the points surveyed on the channel bed, starting from the bank toe (banks are generally excluded from this calculation). A weighted average elevation should be used, taking into account the distance between each pair of surveyed points, if the points are not evenly spaced acreoss the section (Figure B.6).



$$Z_{mean} = \frac{\sum_{i=1}^{n} \left\{ \left[\left(Z_i + Z_{i+1} \right) / 2 \right] \cdot \left(X_{i+1} - X_i \right) \right\}}{\sum_{i=1}^{n} X_i}$$

Figure B.6 Calculation of the Mean bed elevation (Z_{mean}) (by a weighted average of bed elevations in a cross-section.

Longitudinal profile

3. The longitudinal profile is the typical way in which bed elevation is represented at the reach scale. The longitudinal profile of minimum bed elevation can be directly obtained by surveying the deepest points in the bed against the longitudinal distances downstream measured along the thalweg (i.e. the line of minimum bed elevation). A survey of multiple cross-sections is not necessary but, if they are available, the longitudinal profile is obtained by plotting for each cross section the deepest point against the distance downstream.

4. Alternatively, the longitudinal profile of mean bed elevation requires a series of cross-sections to be surveyed along the investigated portion of the river. Cross-sections should be surveyed at sufficiently small intervals to describe changes in bed elevation adequately along the entire investigated reach or a significant portion of it. The longitudinal profile of mean bed elevation is then obtained by plotting the mean bed elevation of each cross-section against the longitudinal distance downstream measured along the channel center line.

Ranges of application

All river types.

Spatial scale

The topographic survey should ideally extend along the entire reach, but if a shorter length is surveyed, survey of a thalweg profile should encompass a sub-reach that is at least 6 - 20 channel-widths in length.

Frequency of measurement

Replication of measurements requires time demanding field topographic surveys, but an interval of about 6 years along selected, representative reaches or sub-reaches is feasible.

16. Channel gradient or bed slope

Definition

“Channel gradient” or “Bed slope” (*S*) is obtained by dividing the difference between the elevations of two points at the upstream and downstream ends of a reach by the length of the main channel mid-line for single thread and anabranching channels or the midline of the braid plain for multi-thread braided and wandering channels.

Relevance

Of the longitudinal profile parameters, channel gradient is the most widely used in hydraulic models and morphological classifications. Channel gradient is used to calculate flow velocity and discharge at various stages, stream power, shear stress, and other parameters that are relevant to channel processes.

Monitoring methods

Field measurement; DEM.

Measurement procedure

1. Measurement of bed slope is directly obtained from the longitudinal profile of bed elevation (see indicator 15), which requires a topographic survey of the channel bed for the investigated reach or for a representative portion.
2. In the absence of a field survey of bed elevation, DEMs or other digital map data (e.g., derived by LiDAR) can provide sufficient resolution to estimate channel gradient. In such a case, the water surface slope can be estimated at low-flow conditions.
3. In both cases, a more detailed estimation of the range of channel gradients within the reach can be obtained by splitting the channel length into a series of sub-reaches to calculate several slopes and then calculating the average. A systematic analysis based on constant horizontal increments, referred to in the literature as 'horizontal slice slope', can be conducted to identify the most appropriate length of the sub-reaches (see for more details Vocal Ferencevic and Ashmore, 2012). In fact, measuring slope over short distances can result in excessive detail that is not related to the scale of the study and may be subject to considerable error, whereas measuring over too large a distance can create a generalized slope that masks elements of real channel form and important local channel-scale slope variation. Because of the sensitivity of estimated slope to the reach length used, a number of different horizontal distances can be tested to identify which might be the most useful for characterising slope at an appropriate level of detail. In any case, an arbitrary decision must be made about the distance over which it is measured.

Ranges of application

All typologies.

Spatial scale

It is necessary to extend the topographic survey of bed elevation for a sufficiently long portion of the reach (ideally it should cover the entire reach), in any case the profile should extend for at least 10 - 20 times the channel width.

Frequency of measurement

Changes in bed slope are an important component of bed-level adjustments that can be tracked by replicating longitudinal profile topographic surveys at regular time intervals.

17. Bankfull channel width

Definition

This indicator is defined as the width of the channel bed, including low flow channel(s) and all instream geomorphic features, in other words the entire width of the channel at the elevation where water would start to spill out onto the floodplain on at least one bank.

Relevance

Channel width is a key parameter to characterize channel morphology and to monitor trends of channel adjustment.

Monitoring methods

Remote sensing–GIS for sufficiently large rivers.
Field measurement: for small rivers.

Measurement procedure

Remote sensing - GIS

1. Orthorectification and georeferencing of each image, followed by digitising of the channel margins and the bankfull axis or center line, defined at the mid-point between the margins of the bankfull channel.
2. Definition of the longitudinal spacing of width measurements (Figure B.7). For an accurate measurement, a longitudinal interval of 0.25÷1 channel width is recommended. This distance can be increased for channels displaying a relatively homogeneous width.
3. Channel width is measured along transects orthogonal to the center-line at each of the previously-defined measurement points. The "Channel width" (*W*) (m) indicator is

the mean of the width measurements obtained along the reach.
4. An alternative way to calculate the mean channel width at reach scale is to calculate the ratio 'channel area / channel length' measured within a GIS. Compared to the previous procedure, a more accurate estimation is obtained, but only one value of mean channel width is obtained with no indication of longitudinal variations in width along the reach.
5. The width of islands is usually excluded from measurements of channel width. However, in such cases, it is useful also to measure the "Total channel width" or "Channel width with islands" (*Wt*) (in m). For anabranching rivers, the channel width is the sum of the mean widths of the active anabranches, while the total width includes the entire corridor of anabranches and islands.

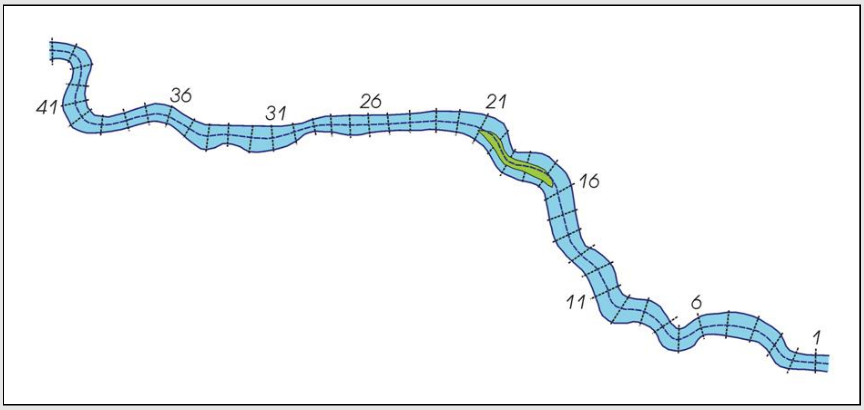


Figure B.7 Measurement of channel width (*W*) from remote sensing – GIS. Segments from 1 to 45 represent the transects of measurement at a constant longitudinal spacing and orthogonal to the channel center line. Between sections 17 and 20, measurement of 'channel width' (*W*) will exclude the island (in green), but the island width is included in the 'total width' (*Wt*).

Field survey
In the case of relatively homogeneous channels in terms of width and characteristics, a representative site (or sub-reach) is selected and a minimum of three measurements are made. In the case of a relatively long reach or a reach with subsections of varying width, measurements should be obtained from representative sites. Cross-section surveys (using a differential GPS or total station) provide the best way to measure channel width while also obtaining other cross-section parameters and bed elevation. When measuring width from remotely-sensed sources, the measurements should be orthogonal to the channel center line.

Ranges of application

All typologies.

Spatial scale

Remote sensing – GIS: reach scale.
Field survey: measurements carried out at representative site(s).

Frequency of measurement

Replication of measurements using remote sensing depends on the availability of new remotely sensed data (aerial photos or satellite images), but an interval of about 6 years is usually feasible.

18. Bankfull channel depth

Definition

Channel depth is the difference in elevation between the water surface and the river bed at bankfull conditions.

Relevance

Bankfull channel depth is a useful characteristic of the geometry of a cross-section. Temporal changes in bankfull channel depth indicate the occurrence of adjustments in bed and/or floodplain elevation.

Monitoring methods

Field measurement: total station/GPS survey for wadable rivers; bathymetric survey for non wadable rivers.

Measurement procedure

1. Measurement of channel depth requires a topographic survey of cross-sections and the identification of the bankfull stage, since it is not associated with the water stage during the field measurement. Bankfull stage is identified for each surveyed cross-section as the maximum stage at which water remains contained within the channel without overtopping the banks and flowing onto the floodplain or, for incised channels, onto the lower terrace.
2. Measurement of the cross-sections. A minimum of 3 representative cross-sections should be surveyed perpendicular to the channel axis (center line), and the sections should be located 0.5 to 2 channel widths apart. Techniques employed for cross-section measurements are the same as for bed elevation. A cross-sectional survey should commence on the floodplain (non-incised streams) or higher terrace (incised streams) surface and proceed across the floodplain, down the bank, across the channel, up the opposite bank and finish on the opposite side of the valley. Depending upon the level of accuracy desired and the site conditions, total stations, differential GPS, laser levels, hand levels, or level lines can be used to accomplish the survey. Laser levels with remote sensors allow a single surveyor to collect cross-sectional data, or several surveyors to collect data on various cross-sections concurrently. Hand levels have reduced accuracy and require at least two surveyors. Stretching a level line across a stream channel and directly measuring vertical distance with a graduated staff is commonly used for cross-section measurement, but errors occur when the line is not perfectly level from left to right bank, or when the line sags in the middle.
3. Once cross-sections have been measured, the maximum depth or the mean depth can be calculated. The "Maximum channel depth" (D_{max}) (m) is obtained as the difference between bankfull stage and the minimum bed elevation (thalweg), whereas the "Mean channel depth" (D_{mean}) (m) is obtained as the difference between bankfull stage and mean bed elevation (Z_{mean}), or as the ratio between of cross-section area to width (Figure B.8). The final value of channel depth is the average of the individual cross-section values.

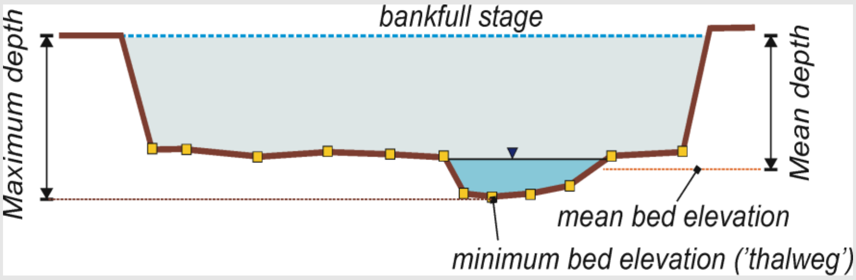


Figure B.8 Measurement of Maximum channel depth (D_{max}) and Mean channel depth (D_{mean}) and from the survey of a cross-section.

Ranges of application

All river types.

Spatial scale

Measurements are carried out at representative sites.

Frequency of measurement

Replication of measurements requires time demanding field topographic surveys, but an interval of about 6 years at selected sites is feasible.

19. Width : depth ratio

Definition

This indicator is defined as the ratio of bankfull channel width to mean channel depth.

Relevance

The width to depth ratio is used for the characterization of the cross-section geometry. It provides information on the hydraulic conditions and therefore is relevant for physical habitats. Changes of width to depth ratio can reflect variations in channel configuration, as a consequence of changes in width and/or depth.

Monitoring methods

Field measurement: total station/differential GPS survey for wadable rivers; bathymetric survey for non wadable rivers.

Measurement procedure

1. Measurement of channel depth requires a topographic survey of cross-sections. It is recommended to define a minimum of 3 representative cross-sections, spaced from 0.5 to 2 channel widths apart, and surveyed perpendicular to the channel axis (center line) (see “Channel depth” for details).
2. The ratio between bankfull channel width and mean channel depth is calculated for each cross section, and the “Width:depth ratio” (*W/D*) is the mean value.

Ranges of application

All river types.

Spatial scale

The parameter is calculated for representative site(s), where channel depth is also measured.

Frequency of measurement

Replication of assessment of this parameter is linked to the repetition of the topographic survey of cross-sections for channel depth measurements.

20. Specific stream power

Definition

Specific stream power is defined as the total stream power divided by the bankfull channel width. Total stream power (Ω) is estimated by combining a morphologically representative discharge (e.g. *Qb* (bankfull discharge), Qp_{median}, $Qp_{2,}$ Qp_{10}) and a measure of channel gradient, using the formula:

$$\Omega = \rho\, g\, Q\, S$$

where: Ω is in W m^{-1}, ρ is the density of water (1000 kg m^{-3}), g is acceleration due to gravity (9.8 m s^{-2}), Q is discharge (in m^{3} s^{-1}) and S is bed slope (in m m^{-1}). For general application, including at sites where only short flow records are available, Qp_{median} is recommended as the discharge estimate.

“Specific stream power” (ω) (W m^{-2}) is calculated as $\omega = \Omega/W$, where W is the bankfull channel width (m).

Relevance

Specific stream power is an indicator of river energy, and is useful for channel / floodplain classification. It is also relevant to biological conditions as it provides information on hydraulic properties and therefore on physical habitat conditions.

Monitoring methods

Data series of annual peak discharge are required to estimate the morphologically relevant discharge; *Field measurement* (or DEM) to assess channel gradient; *remote sensing – GIS* or *field measurement* to assess channel width.

Measurement procedure

To assess specific stream power we refer to the assessment of channel gradient (see indicator 16) and bankfull channel width (see indicator 17).

Ranges of application

All river types.

Spatial scale

Reach.

Frequency of measurement

The same frequency as for channel gradient and bankfull channel width.

21. Variability of cross section

Definition

This indicator evaluates the variability in channel depth along the cross section in relation to what might be expected for the channel type of the investigated reach.

Relevance

The natural heterogeneity of forms and surfaces within the channel cross-section, which are representative of the form and complexity of the bed, has several implications in terms of physical habitats and natural functioning of dynamic processes.

Monitoring methods

Field survey: visual assessment (qualitative); *remote sensing–GIS:* estimation of length of unaltered portions (quantitative).

Assessment procedure

1. A field evaluation is carried out at the scale of some representative sites. In the absence of qualitative or quantitative field observations, the variability in channel depth can be deduced to some extent from the frequency and types of geomorphic units present. In addition, alteration of the natural, expected heterogeneity of forms and surfaces for a given river type caused, for example, by artificial elements or maintenance interventions can also be assessed.
2. Identification by remote sensing of portions of the reach where variability in channel depth exists or, equivalently, where this variability is assessed as altered. The percentage of the reach length with the expected natural "Variability of cross-section" (*Vcs*) (%) is then evaluated by GIS.
3. For a more detailed assessment of cross section complexity, some quantitative parameter from the survey of a series of cross sections along the reach can be analyzed (e.g., coefficient of variation of depth, cross-section asymmetry, etc.).

Ranges of application

All river types. The indicator should be evaluated in relation to the expected natural variability for the given river type. For example, steep, bedrock reaches or low-gradient single-thread reaches may have a natural absence of variability of cross section.

Spatial scale

Reach.

Frequency of measurement

Replication of the assessment can be periodically carried out by a new field survey and/or when a remotely sensed images are available, particularly in the case that new human impacts exist along the reach.

Bed substrate (including vertical connectivity)

22. Bed sediment size

Definition

This indicator evaluates the dominant size of the bed sediment.

Relevance

The calibre of bed sediment is a fundamental parameter when characterizing channel type, deriving bed roughness, and estimating critical shear stress for bed motion and bedload. It is also an important property of physical habitats.

Monitoring methods

Field measurement: identification of bed sediment size needs a field assessment and, for accurate assessment, bed material sampling.

Measurement procedure

1. The characteristic calibre of bed sediment needs, at a minimum, to be distinguished to the qualitative level of bedrock, boulders, cobbles, gravel, sand and silt, clay. This

information is usually collected in the field, although bedrock- or boulder-dominated reaches are sometimes distinguishable on aerial imagery. This information is collected at reach scale: if some variability of bed sediment is observed, the predominant size classes should be noted. Where there is a mix of two dominant sediment sizes, a combined descriptor can be used such as boulder-cobble.

2. Given that bed sediment size is a crucial property for channel morphodynamics, sediment transport, and physical habitat characters, collection of some representative sediment samples from the field is strongly recommended. The following parameters can be extracted if a complete particle size distribution is available: (1) Median particle size / D_{50}; (2) Sorting coefficient (width of the particle size distribution); (3) Skewness (asymmetry of the distribution); (4) Kurtosis (peakedness of the distribution). Detailed recommendations concerning bed sediment sampling and analysis can be found in REFORM Deliverable 2.1, Part 2, Annex D.

Ranges of application

All rivers except bedrock channels.

Spatial scale

The characteristic calibre of bed sediment at a qualitative level is collected at reach scale. Bed sediment sampling for detailed analysis is conducted at representative sites.

Frequency of measurement

Changes in bed sediment size normally occur over a relatively longer time scale compared to other indicators. This indicator can be conveniently collected once to integrate the characterization of river conditions, or can be observed periodically at a relatively low frequency to monitor any changes.

23. Bed armouring

Definition

Bed armouring refers to the presence of a coarser, tightly packed, surface layer of sediment compared to the sub-layer.

Relevance

Alteration of bed structure may have significant effects on incipient motion and transport of sediment transport, on vertical hydrological connectivity, and thus on ecological conditions.

Monitoring methods

Field survey: visual assessment (qualitative) or comparative sediment sampling of surface layer and sub-layer (quantitative).

Assessment procedure

1. A field evaluation is carried out at the scale of one or more representative sites. Presence and extension of armouring is visually assessed.

2. A quantitative assessment of armouring requires sediment sampling and measurements of the surface layer and sub-layer (see Deliverable D2.1, Part 2, Annex D for recommended methods). The “Armour ratio” (*Ar*) can be calculated as the ratio between D_{50} (median diameter of bed sediment) of the surface layer divided by D_{50} of the sub-layer. Two conditions are normally defined: (1) weak (or mobile) armour, when the surface layer is slightly coarser than the sub-layer and is mobilised during floods close to bankfull conditions; (2) static armour, when a marked difference in sediment size exists, and the surface layer is mobilized only during exceptional floods. An armour ratio higher than 3 is often assumed to indicate static armour conditions (Hassan, 2005).

3. Based on visual observations and quantitative assessment, the following three broad cases can be identified: (1) absent: no obvious difference between surface and subsurface bed sediment calibre, i.e. natural heterogeneity of bed sediments in relation to the different sedimentary units (bars, channel bed, pools, riffles, etc.); (2) present: surface bed sediment coarser than subsurface across > 50% of the bed; (3) severe: D_{50} surface >> 3 times D_{50} subsurface across >50% of the bed.

Ranges of application

Armouring is only observed on rivers with relatively coarse bed material (gravel, cobble). In the case of a confined stream with coarser bed sediment (boulders), armouring is not considered, as confined channels with a mobile bed have a naturally strong heterogeneity of sediments. It is not evaluated for bedrock or sand-bed rivers, or for deep channels when observation of the bed is not possible.

Spatial scale

Representative site(s).

Frequency of measurement

Replication of the assessment can be carried out periodically by a new field survey.

24. Clogging

Definition

Clogging or burial refers to an excess of fine sediments causing interstitial filling of the coarse sediment matrix and potentially smothering of the channel bed ("blanket": Brierley & Fryirs, 2005, or "embeddedness": Sennatt et al., 2008).

Relevance

Clogging is important because of its effects on the sediment structure of the bed and its physical habitats, which have negative ecological consequences.

Monitoring methods

Field survey: visual assessment (qualitative).

Assessment procedure

1. A field evaluation is conducted at the scale of one or more representative sites. Presence and extension of clogging is visually assessed. Clogging can be normal in particular situations (e.g. in the bottom of pools or along a stream close to hillslopes composed of fine sediment), but it is considered an alteration when it is widespread through a reach.
2. A more quantitative assessment of clogging can be based on an evaluation of the percentage of the bed surface where clogging is visually observed across an investigated site. Pools (where clogging is often observed) are normally excluded. The following broad classes can be used: (1) *absent*: no obvious increase in sand and finer particle content between surface and subsurface bed sediment; (2) *present*: higher sand and finer particle content in surface than sub-surface sediment; (3) *severe*: subsurface intergranular spaces completely clogged with sand and finer particles across > 50% of the bed; (4) *very severe*: sand and finer sediment layer completely burying > 90% of the gravel river bed.

Ranges of application

Not evaluated for bedrock or sand-bed rivers, or for deep channels when observation of the bed is not possible.

Spatial scale

Representative site(s).

Frequency of measurement

Replication of the assessment can be carried out periodically by a new field survey.

B2.2 Indicators of artificiality

Most artificial elements may have multiple effects on different components of morphological conditions (longitudinal or lateral continuity, channel pattern, profile / cross section, substrate). In this section, a list of the main artificial elements is reported, with the information that should be acquired during a monitoring activity, particularly when new artificial elements are added or existing elements are removed.

Methods and data sources for monitoring artificial elements include a combination of *remote sensing*, *database (layer) of interventions*, *field survey*, *information from public agencies on maintenance practices*.

1. Dams

Definition

Dams are the hydraulic structures that have the greatest impact on longitudinal continuity of water and sediment.

Information required for monitoring activity

(1) Location; (2) year of implementation; (3) dam height; (4) dam type; (5) use (hydropower, reduction of peak flows, water abstraction, etc.); (6) amount of reduction of peak flows and/or other alterations of flow regime; (7) sediment management measures, i.e. measures allowing for the flux of bedload downstream.

Dam

2. Diversion channels and spillways

Definition

Diversion channels and spillways are other hydraulic structures that regulate flows.

Information required for monitoring activity

(1) Location; (2) year of implementation; (3) type; (4) use (reduction of peak flows, water abstraction); (5) amount of reduction of peak flows and/or other alterations of flow regime; (6) sediment management measures.

Diversion channel

3. Retention basins

Definition

Retention basins are implemented to reduce flood peaks, and have consequent impacts on the flow hydrograph and in some cases on sediment flow.

Information required for monitoring activity

(1) Location; (2) year of implementation; (3) type (lateral or in-channel); (4) amount of reduction of peak flows; (5) measures of sediment management.

Retention basin

4. Check dams and weirs

Definition

Check dams and weirs are transverse structures of a smaller size than dams but that may still have relevant effects on longitudinal continuity. These structures may have different purposes: (1) reduction of sediment discharge to downstream reaches (retention check dams); (2) reduction of bed slope or bed level stabilization (consolidation check dams); (3) water abstraction (weirs).

Information required for monitoring activity

(1) Location; (2) year of implementation; (3) height; (4) type; (6) amount of abstracted water (in case of abstraction weirs); (7) sediment management measures, i.e. measures allowing for the flux of bedload downstream.

Check dam

Weir

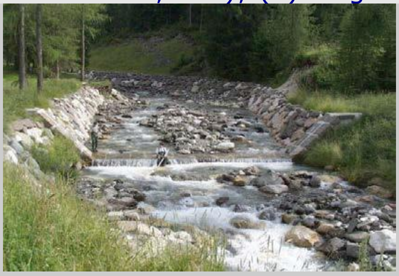
5. Sills, ramps, and revetments

Definition and impacts

Other bed stabilization structures include sills, ramps, and revetments.

Information required for monitoring activity

(1) Location; (2) year of implementation; (3) type (permeable or impermeable revetments, etc.); (4) length.



Sill

Ramp

Revetment

6. Crossing structures

Definition

Crossing structures (such as bridges, fords, and culverts) may interact with water flow, sediment and and wood transport.

Information required for monitoring activity

(1) Location; (2) year of implementation; (3) type of crossing structure and construction material; (4) number of piers (in case of bridges).

Bridge

Ford

Culvert

7. Bank protection

Definition

Bank protection consists of longitudinal structures directly protecting the bank from erosion, but also including transverse structures (groynes) that deflect erosive flows and so reduce their direct impact on the banks.

Information required for monitoring activity

(1) Location; (2) year of implementation; (3) type (walls, rip-rap, revetments, bioengineering, groynes, etc.) and orientation (longitudinal, transverse, oblique); (4) size (height, longitudinal length).

Bank protection

8. Artificial levées

Definition

Artificial levées or embankments are earth or concrete longitudinal structures located at varying distances from the channel banks.

Information required for monitoring activity

(1) Location; (2) year of implementation; (3) type (concrete, earth, reinforced soil, etc.); (4) distance from the banks (set-back, close, bank-edge); (4) size (height, longitudinal length).

Artificial levées

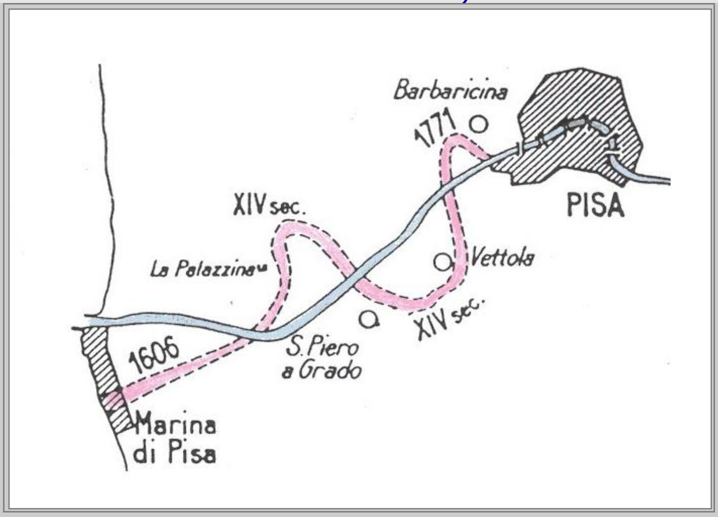
9. Artificial changes of river course

Definition

This category includes meander cutoffs, channelization and channel straightening.

Information required for monitoring activity

(1) Location; (2) year of implementation; (3) type; (4) longitudinal extent (length of the artificial reach before and after the intervention).



Artificial changes of river course

10. Sediment removal

Definition

Sediment removal may heavily impact channel morphology by modifying the cross-section geometry and bed elevation, reducing available sediment volumes, removing geomorphic units and associated physical habitats, and causing alterations to the bed structure.

Information required for monitoring activity

(1) Location; (2) year of implementation; (3) type (deep pit, bar scalping, bar-edge excavation, etc.); (4) size (length and width of the excavation or of the reach subject to sediment removal); (5) estimation of the volume of sediment removed.

Sediment removal

11. Wood removal

Definition

Removal of wood is often carried out in conjunction with sediment removal or vegetation cutting (see indicators of riparian vegetation).

Information required for monitoring activity

(1) Location; (2) year of intervention; (3) length of the reach subject to wood removal; (4) estimate of the volume of removed wood.

Wood removal

B.3 Evaluation of monitoring results

Evaluation of monitoring results can be conducted in various ways. A first option is to analyse monitoring results by visualizing the temporal trend of the selected monitoring indicator. The temporal trend is compared to the past trajectory of a given parameter to understand whether changes are still occurring following such trajectory, or a new trend is observed. A second approach is to use monitored data to periodically apply a method for assessing morphological conditions that summarises the monitoring results by a synthetic index. These two approaches are described in the next two sections.

B3.1 Monitoring and analysis of temporal trends of morphological indicators

This approach employs periodic measurements of some selected morphological parameters or indicators in order to visualise and analyse their temporal trends. This approach is particularly suitable for a detailed investigation that aims to quantify changes and identify their causes.

Selection of the monitored parameters is case-specific and depends upon various factors including: (1) the objectives of the monitoring; (2) the morphological characteristics of the investigated reach; (3) the type of pressure for which a response is being investigated, since the parameters that are most sensitive to the investigated pressure need to be selected.

In general, any indicator described in the previous section could be monitored. However, the following parameters are normally the most relevant:

- Pattern (sinuosity, braiding, or anabranching indices, depending on channel type): these support monitoring of possible adjustments in channel planform and river type in response to some pressure or intervention. Their changes can be measured by remote sensing if a new image is available, or by field survey (particularly for small channels).
- Longitudinal profile / cross section (bed elevation, channel gradient, bankfull channel width, bankfull channel depth, width:depth ratio): these support monitoring of adjustments in bed elevation and channel width in response to some pressure or intervention. Monitoring depends on conducting a new field survey (except channel width that can be measured by remote sensing).
- Bed substrate (armouring, clogging): these can be important indicators of the influence of high impact transverse structures such as dams, retention check dams, and hydropower plants. Visual assessment can be used to establish the existence and longitudinal extent of the alteration but in particularly problematic cases, a quantitative evaluation of the degree of armouring could be required.

The required temporal frequency of the measurements also varies depending on the type of monitoring and on the characteristics of the pressures.

The output of this type of monitoring is the reconstruction of the temporal trend of a selected set of parameters. The evolutionary trajectory of those parameters allows the duration and intensity of the morphological changes to be established and the possible factors influencing such evolution to be understood (i.e., through the construction of potential cause-effect relationships).

For a given morphological parameter (e.g., bed elevation, bankfull channel width, etc.), two types of representation can be constructed: (1) a *spatio-temporal distribution,* created by plotting the parameter against distance downstream (at reach scale) for different years; and (2) a *temporal trend*, by plotting the parameter “at-a-station” (i.e., at a specific cross-section) or the reach-averaged value of the parameter against time. The first type of representation allows visualisation of the spatial variation of a given parameter and, at the same time, comparison of values at the same spatial position in different years (Figure B.9A). The second type of representation provides information on the temporal trend or trajectory of the parameter (Figure B.9B).

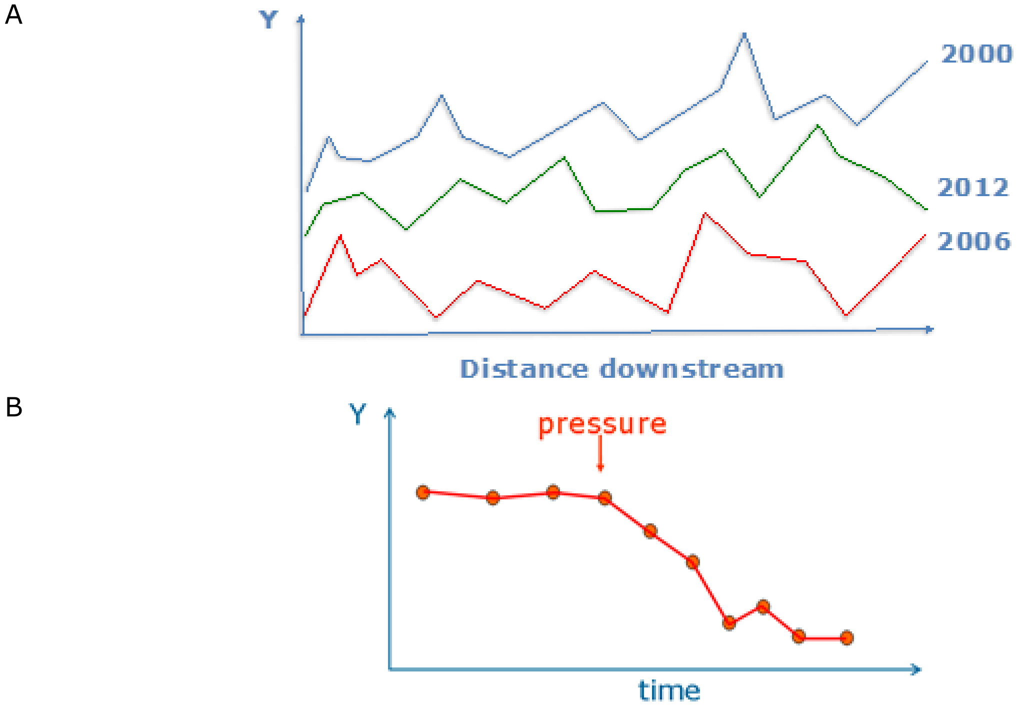


Figure B.9 Two possible ways to represent and visualise temporal changes of a morphological parameter. A) Spatio-temporal distribution; B) Temporal trend.

B3.2 Periodic evaluation by assessment tools

A second option for analysing monitoring data is to periodically repeat the application of an assessment method that provides a synthetic index of morphological conditions. Repeat values of the synthetic index may reveal changed values induced by an intervention or restoration measure, or occurring independently of any interventions.
Among the various available morphological assessment methods, the Morphological Quality Index (*MQIm*), has been developed for this purpose. The *MQIm* is a tool for monitoring morphological conditions in the short term, i.e. to evaluate any temporal *tendency in morphological conditions* (enhancement or deterioration).
A detailed description of the *MQIm* and the ways in which it differs from the *MQI* are reported in **Deliverable D6.2 Part 3**. The *MQIm* and the *MQI* are complementary rather than alternative indices. The *MQI* provides an overall evaluation of morphological conditions and is suitable for classifying and monitoring morphological state (for example, achievement of a good morphological state can be assessed using this index), whereas the *MQIm* provides an assessment of any short-term trend in morphological quality.

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ANNEX C Indicators of riparian vegetation

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Introduction

Riparian vegetation is a key component of river systems, affecting and responding to fluvial processes (Corenblit et al., 2007, Gurnell, 2013; Gurnell et al., 2015), and significantly contributing to trajectories of river changes and recovery from human interventions (González del Tánago et al., 2015). At each spatial scale, different key processes and controls affecting riparian vegetation features can be recognized, resulting in different vegetation units (see Table C.1) that can be used to assess riparian conditions and human pressures (see Table C.2).

The Water Framework Directive includes "structure of the riparian zone" as a hydro-morphological quality element for the classification of ecological status or rivers, taking part of the morphological conditions of water bodies. Thus, the development of practical tools to characterize and monitor the riparian vegetation is needed (González del Tánago & García de Jalón, 2006; Rinaldi et al., 2013), and this task has been fully addressed by the REFORM Project within the Work-packages 2 and 6.

In this document, some indicators to assess the aforementioned vegetation units and features at different spatial scales are developed (Table C.3), whose relevance and monitoring procedure are briefly addressed. The applicability of the proposed indicators are similar in all the cases, as they concern to the cases where the riparian corridor exists, which more likely occurs along partly confined and unconfined valleys. In confined valleys the riparian corridor hardly exists, and the riparian vegetation is naturally restricted or very scarce. Most of the proposed indicators may be assessed by visual appraisal on aerial photographs. Some of them may also be quantified automatically (vegetation patches as landscape metrics, McGarigal and Marks,1994; Fernandes et al., 2011) whereas others require field work (e.g. species composition, age diversity, recruitment).

In general, vegetation changes gradually following natural growth and succession stages (see Fig. C.1) although they may occur abruptly as a consequence of fluvial disturbances (e.g. flood events, Corenblit et al., 2007) or human interventions. Two times for monitoring the reported vegetation indicators have been proposed, which have been related to the revision of the River Basin Management Plans (RBMP) within the WFD. Once the riparian vegetation has been properly characterized, some indicators are proposed to be monitored each time the RBMP is revised (i.e., each 6 years), whereas others have been proposed to be monitored more frequently (i.e., each 3 years) as they can more closely reflect the influence of fluvial disturbances (e.g. flood events) or human interventions, including restoration measures.

Table C.1 Multi-scale key processes and controls affecting species composition and structure of riparian corridors.

SPATIAL UNIT	KEY PROCCESS FOR VEGETATION	VEGETATION CONTROLS	VEGETATION UNITS
REGION:	Broad Hydro-geomorphic processes	Bioclimatic Zones Biogeographical Regions (Geology, Relief, Potential Flora)	***Vegetation Zones***
CATCHMENT	Precipitation Temperature regime Evapotranspiration	Geology Water availability potential Evaporative potentials	***Riparian Plant Formations***
LANDSCAPE UNIT	Hillslope Runoff Aquifer storage Sediment supply	Hydrologic regime Soil texture Land Use Valley dimensions	***Riparian Plant Associations***
RIVER SEGMENT	Flow regime Floodplain Infiltration Water table fluctuation Sediment stability Floodplain degradation/aggradation Large wood supply	Flood frequency, magnitude and timing Base flow Channel entrenchment Soil water availability Substratum permeability Alluvial depth	***Riparian Plant Communities*** ***Vegetation functional zones***
RIVER REACH	Flood disturbance Soil moisture retention Local erosion /deposition processes	Inundation frequency Shear stress Sediment size Sediment cover	***Vegetation Mosaics, Patches*** ***Vegetation assemblages, guilds*** ***Vegetation functional zones***
RIPARIAN AND FLOODPLAIN GEOMORPHIC UNITS **CHANNEL GEOMORPHIC UNIT**	Water flowing Sediment stability Shadowing	Water velocity Water depth Light Water Temperature	***Vegetation Mosaics, Patches*** ***Aquatic Vegetation Communities, Populations***

Table C.2 Multi-scale examples of vegetation indicators of functionality and artificiality reflecting potential effects of pressures and impacts in riparian corridors.

SPATIAL UNIT	VEGETATION INDICATOR		PRESSURES / IMPACTS
	FUNCTIONALITY	ARTIFICIALITY	
REGION:	Vegetation Types - Forest/Shrub Vegetation Type - Dominant species	Anthropogenic vegetation types	Large scale Land cover changes
CATCHMENT	Riparian forest Types - Dominant species	Anthropogenic Riparian forests	Large scale Land cover changes
LANDSCAPE UNIT	Riparian / Floodplain vegetation Associations - Dominant species - Diversity	Changes in species composition/abundance % Alien species Valley floor occupation	Agriculture Afforestation Grazing Urbanization Groundwater depletion
RIVER SEGMENT	Corridor features: - Dimensions (average width) - Height and Coverage - Longitudinal connectivity Transversal zonation (lateral/functional zones) - Average width - Species composition - Vegetation coverage	Corridor narrowing/widening Changes in coverage Fragmentation Transversal homogeneity (no different lateral/functional zones) % non-native species Vegetation encroachment	Flow regulation Lateral barriers Channelization works Floodplain occupation: Agriculture Grazing Urbanization Poplar plantations
RIVER REACH **RIPARIAN AND FLOODPLAIN GEOMORPHIC UNITS**	Location (distance and elevation from base flow level) Species composition and Age-class structure: Recruitment and early stages (< 5y)) Juveniles (5-10 y) Mature forest (10-50 y) Old forest (> 50y)	Changes in location due to human intervention Absence of early stages of pioneer species Dominance of late seral-species % Dead trees Dominance of xerophytes herbaceous communities	Flow regulation Lateral barriers Channelization works Pavement, soil sealing Bank elevation Fillings, excavations Water pollution
CHANNEL GEOMORPHIC UNIT	Coverage Species composition	Changes in coverage Changes in diversity	Flow regulation Water drawl Water pollution Channelization Dredging

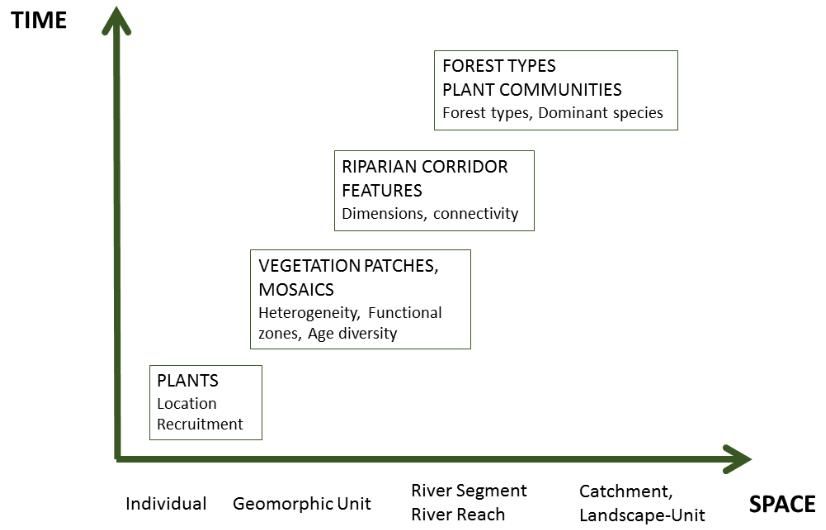


Figure C.1 Schematic representation of spatial scales and time to full develop riparian vegetation units and features.

Table C.3 Multi-scale riparian vegetation indicators proposed for characterization and monitoring purposes.

Spatial unit	*Assessed criteria*	*Vegetation indicator*	*Metrics*
Catchment Landscape unit	Vegetation type	Forest type	Categorical
		Plant formations	Categorical
		Plant associations	Categorical
River segment	Riparian corridor features	Average riparian corridor width	m
		Longitudinal continuity	% of channel bank
		Coverage	% land cover
		Species composition	Categorical
	Pressures	Fragmentation	% of channel bank
		Invasive species	Number
		Land use /occupation	% area
River reach	Patch features	Number of patches	Number
		Average size	m^2
		Shape	Area (m^2)/perimeter (m)
	Age diversity	Age classes	Abundance of classes -Pioneers (1-2 y) -Early stages (< 5y) -Juveniles (5-10 y) -Mature forest (10-50 y) -Old forest (> 50y)
	Hydromorphological interactions	Functional zones	% riparian zone under distinct functional zones: - Fluvial disturbance, erosion - Fluvial disturbance deposition - Inundation - Groundwater

C.1 Catchment/Landscape unit scale

Vegetation type, plant formation and plant associations

Definition

These characteristics represent a broad scale description of riparian vegetation, indicating general attributes of plant communities. *Vegetation Type* is indicative of the forest typology based on the dominant species (e.g., coniferous vs. deciduous forest). *Plant formations* refers to the general morphotype of vegetation communities (e.g. shrub, tree galleries) whereas *Plant associations* intend to explicit the species composition of dominant species (e.g., riparian mixed galleries with *Betula* sp. and *Fraxinus excelsior*).

Relevance

Represent the first step in riparian vegetation characterization and are indicative of biogeographic and climatic (i.e., altitude) conditions. They are essential to compare current status with potential status of vegetation, to understand composition and structure of plant communities at smaller scales and to exchange experiences on riparian vegetation management and restoration across different regions.

Monitoring methods and measurement procedure

Literature review and General Data Base from Corine Land Cover, GlobCover Land Cover V2 that is also a global land cover map (http://due.esrin.esa.int/globcover/). References of Forest types can be found in EEA (2006), and plant associations can be defined according to the Habitat Directive (main systems of habitat and vegetation classification employed in Europe (EUNIS/CORINE and Natura 2000).

Ranges of application

All rivers.

Spatial scale

Catchment and Landscape Unit scale, although they can be also used as the first step in characterizing riparian vegetation structure at smaller scales (i.e., river segment, reach).

Frequency of measurement

These attributes represent basic information of vegetation and remain quite stable over time. In absence of direct human interventions, their monitoring can be done every six years.

C.2 River segment scale

Average riparian corridor width

Definition

The indicator refers to the average dimensions in width of the lateral bands along the channel covered by riparian vegetation, which are clearly differentiated from the adjacent land cover or uses. It could be estimated for each side of the channel (i.e., left and right band) or for the river corridor as a whole. It largely depends on valley type and river size.

Relevance

One of the most important features of the lateral dimension of the river corridor, indicating the magnitude of the role of vegetation influencing flow resistance and fluvial processes (sediment erosion, deposition). It is indicative of the integrity of the river corridor (riparian width or current dimensions) vs. floodplain width or potential dimensions) and their associated ecosystem functions (e.g., retention of nutrients, habitat and corridor for birds, wildlife, etc.).

Monitoring methods

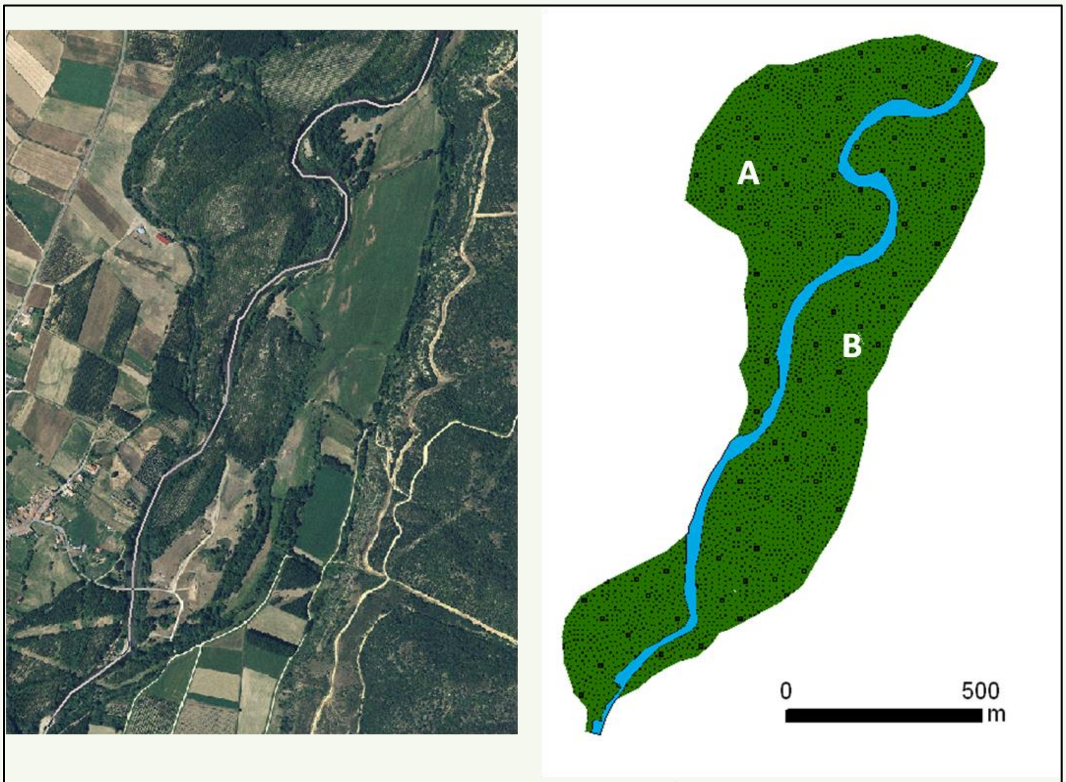
Remote sensing – GIS: direct width measurements on aerial photographs.

Measurement procedure

1. Identification and delimitation of the riparian corridor, considering each margin

along the active channel (Fig. C.2: A and B).

2. Measurements of riparian corridor width along perpendicular transects to the channel, and estimation of average values for the respective river segment.



Average riparian corridor width= (A+B)/(2*length)
e.g. 734243.5 / (2*2372.3)= 154.8 m

Figure C.2 Example of delineation of riparian corridor where width measurements may be carried out.

Ranges of application

All rivers with distinct riparian corridor (i.e., partly confined or confined segments). In confined valleys the riparian corridor is naturally reduced or does not exist.

Spatial scale

River Segments, Reaches. It should be referred to a certain length of the channel.

Frequency of measurement

Once every six years or after significant flood events.

Pressures

Agriculture, urbanization, infrastructures, flood defence works, etc. often occupy the lateral dimension of the riparian corridor reducing its width. As a general rule, in partly confined or unconfined rivers any value of riparian corridor width smaller than 2 times the channel width, or less than 30-45 m on large rivers, should be considered as artificially reduced.

Longitudinal continuity

Definition

The indicator refers to the proportion of the length of the channel maintaining continuous riparian corridor with relative natural and homogeneous conditions.

Relevance

The longitudinal continuity of the riparian corridor assures the continuity of its hydromorphological and ecological functions along the channel. The opposite attribute of longitudinal continuity is fragmentation.

Monitoring methods

Remote sensing – GIS: direct measurement or appraisal on aerial photographs.

Measurement procedure

1. Delineation of river´s margins distinguishing the length occupied by riparian corridor from the length of the discontinuities.
2. Longitudinal continuity estimation based on the proportion of bank length with riparian vegetation in each channel side (Fig. C.3).

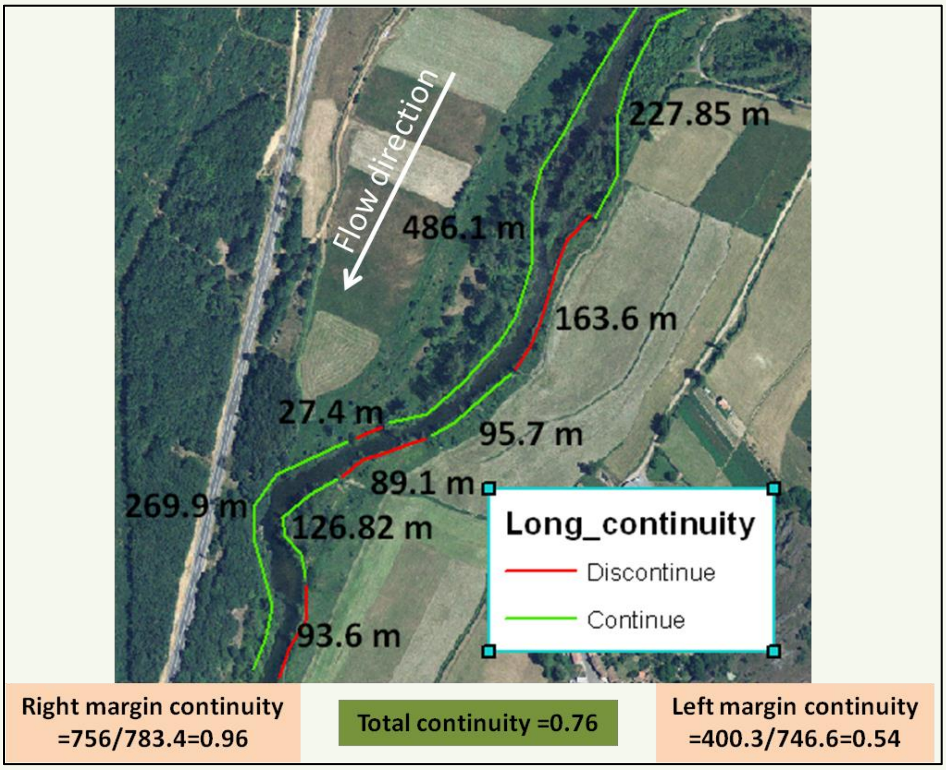


Figure C.3 Schematization of the measurement procedure of riparian corridor continuity.

Ranges of application

All rivers with distinct riparian corridor (i.e., partly confined or confined segments).

Spatial scale

River Segment, River Reach.

Frequency of measurement

In absence of human interventions, once every six years.

Pressures

Floodplain occupation or other human interventions affecting the riparian zones usually result in fragmentation of vegetation forest, decreasing its longitudinal continuity. Fragmentation should be assessed by the number of open spaces along the corridor and by the intensity of these open spaces acting as barriers for the organisms. Thus, fragmentation is always relative to the specific communities or species it is indicative for.

Coverage

Definition

Coverage of riparian corridor corresponds to the fraction of ground covered by vegetation.

Relevance

It quantifies the spatial extent of vegetation and also indicates the percentage of bare soil within the riparian corridor.

Monitoring methods

Remote sensing – GIS: direct estimation on aerial photographs.

Measurement procedure

1. Direct estimation from observations of ortophotos, distinguishing vegetation coverage from open spaces
2. Indirect estimation, as this variable is highly related with NDVI (*Normalized Difference Vegetation Index*) easily estimated by remote sensing with automated procedures.

Ranges of application

All rivers with distinct riparian corridor (i.e., partly confined or confined segments).

Spatial scale

River Segment, Reach.

Frequency of measurement

Vegetation Coverage could change gradually (i.e., vegetation growth) or sharply because of fluvial disturbances (i.e., floods). In absence of human interventions, it could be monitored every three years, being related with longitudinal continuity.

Pressures

Vegetation management, grazing or other human interventions may reduce natural coverage of riparian vegetation. By the contrary, damming and flow regulation may artificially increase riparian vegetation coverage after promoting vegetation encroachment below dams.

Species composition and vegetation structure

Definition

It indicates the range of species that are present in the riparian zones, and their spatial structure. Complementary to this characteristic could be the species richness (number of species) and percentage of native species.

Relevance

The species composition assesses the naturalness of the riparian vegetation. The spatial structure of vegetation stands may be associated to functional zones indicative of hydromorphological processes and vegetation interactions. It also defines the importance of exotic or invasive species and abundance of mats, reeds, nitrophilous or ruderal species.

Monitoring methods and measurement procedure

Field survey: identification and checking species composition of vegetation stands (qualitative) and identification of vegetation character (i.e., native, exotic, invasive, nitrophilous or ruderal species). Spatial distribution should be assessed by identifying functional zones where fluvial disturbance with erosion and deposition processes are dominant, or where riparian soil moisture is primarily replainished by inundation or groundwater.

Ranges of application

It could be assessed in all type of rivers.

Spatial scale

River Segment, Reach.

Frequency of measurement

Description of Species composition and vegetation structure is essential to characterize the riparian corridor, and should be done every three years, to monitor the conservation status and potential of species invasion.

Pressures

Poplar plantations may exist within the riparian corridor, replacing natural riparian vegetation. Other pressures such as flow regulation or channelization works that reduce the frequency of fluvial disturbance may gradually promote the introduction of non-riparian species as well as the expansion of other exotic or invasive species. Water pollution or soil fillings may also promote the growth of nitrophilous or ruderal species.

C.3 River reach scale

Number of vegetation patches

Definition

Number of identifiable vegetation patches relatively distinct from the riparian matrix.

Relevance

This indicator broadly describes the heterogeneity, spatial distribution and continuity (vs. fragmentation) of riparian vegetation.

Monitoring methods

Remote sensing – GIS.

Measurement procedure

1. The lateral limits of the riparian zone are manually digitalized for both riverbanks. Polygons of homogeneous strata of riparian vegetation – riparian patches – should be delineated and classified into riparian vegetation cover classes (e.g. trees, shrubs, herbaceous). This could be done using visual screening of image features, namely the spatial variation in pixel intensity pattern and the local contrast (grey level differences). For instance, tree cover class had a higher variability in these textural features than the other classes, while the herbaceous class is the most homogenous of all.
2. Once the polygons are digitized, the number of patches are counted either as the total number or number of each class of patches.

Ranges of application

All rivers with distinct riparian corridor (i.e., partly confined or confined segments).

Spatial scale

River segment, Reach.

Frequency of measurement

Number of patches may be reduced by vegetation growth or encroachment, or increased by vegetation fragmentation due to many reasons. For regular monitoring it may be assessed every 6 years, or after significant human intervention or flood event.

Patch size: average and variation coefficient

Definition

It indicates the size and homogeneity of vegetation patches and represent a landscape indicator potentially related to geomorphic diversity.

Relevance

It is related with the heterogeneity in the structure of the riparian vegetation.

Monitoring methods

Remote sensing – GIS.

Measurement procedure

1. The first step is the same than in the case of "Number of patches", the delineation of features.
2. Once the polygons are digitized, areas could be calculated and also the coefficient of variation based on vegetation type. This task could be easily done by using the "Patch Analyst" tool (vector Format) for ArcGis.

Ranges of application

All rivers with distinct riparian corridor (i.e., partly confined or confined segments).

Spatial scale

River segment, Reach.

Frequency of measurement

For regular monitoring it may be assessed every 6 years, or after significant human intervention or flood event.

Patch shape

Definition

The shape of patches describes relationships between perimeter and area. It is indicative of irregularity or complexity of current shape of vegetation patches by rapport to circular or rectangular shapes having the same perimeter or area. In particular, the indicator of shape is the *Mean Shape Index*: a configuration landscape metric which relates the patch area and its perimeter.

Relevance

The shape of vegetation patches is indicative of their edge effect. Convoluted shapes indicate large boundaries, expressing high interactions with the adjacent matrix.

Monitoring methods

Remote sensing – GIS.

Measurement procedure

1. The first step is the delineation of patches.
2. Once the polygons are digitized, mean shape indexes of each vegetation type could be automatically calculated by using the "Patch Analyst" tool (vector Format) for ArcGis.

Ranges of application

All rivers with distinct riparian corridor (i.e., partly confined or confined segments).

Spatial scale

River segment, Reach.

Frequency of measurement

For regular monitoring it may be assessed every 6 years, or after significant human intervention or flood event.

Age diversity

Definition

Age diversity refers to the number of age classes exhibited by the existing riparian vegetation. As a minimum, four or five age classes should be differentiated: recruitment or seedlings, young forest, mature forest and old forest. Other categories can be also considered: pioneer (1-2 y), early growth/stages (< 5y), juvenile (5-15 y), mature forest (15-50 y), and old forest (> 50y). For each species, size of plants corresponding to these ages (in terms of total height or stem diameter) should be established.

Relevance

Age diversity is indicative of the health of the riparian zone and the degree to which it is being modified and turned over by fluvial disturbances. The coexistence of diverse age classes reflects sustainability of riparian vegetation under current hydrological conditions, and the recruitment of pioneer species is indicative of maintenance of mechanisms of natural regeneration.

Monitoring methods and measurement procedure

Field survey is necessary to record age classes of plant species. Age categories can be assessed by height or stem diameter measurements.

Ranges of application

All rivers with distinct riparian corridor (i.e., partly confined or confined segments).

Spatial scale

River segment, Reach.

Frequency of measurement

Once every six years or after significant flood event. Recruitment of Salicacea, as the more representative pionner vegetation of riparian forest in European rivers, could be monitored more frequently, once every 3 years or after significant fluvial disturbances or rehabilitation measures, as it represents a good indicator of human pressures and restoration success.

Functional zones

Definition

Functional zones refer to the distinct bands or areas covered by riparian vegetation supporting different hydromorphological interactions: (1) Fluvial disturbance dominated areas with predominant erosion processes resulting in coarse substratum; (2) fluvial disturbance dominated areas with predominant deposition processes resulting in finer substratum; (3) inundation dominated areas with low erosion-deposition effect; (4) groundwater or soil moisture regime dominated areas (Gurnell et al., 2015).

Relevance

These four functional zones usually exist along the riparian corridors, with different extension according to river typology and biogeographic context. They are indicative of full river functioning and may be used as references for assessing riparian vegetation status and vegetation recovery after restoration measures.

Monitoring methods and measurement procedure

Field surveys are necessary to identify predominant fluvial interactions affecting riparian vegetation composition and structure. Delineation on aerial photographs is necessary to assess the percentage of area occupied by each functional zone (Fig. C.4).

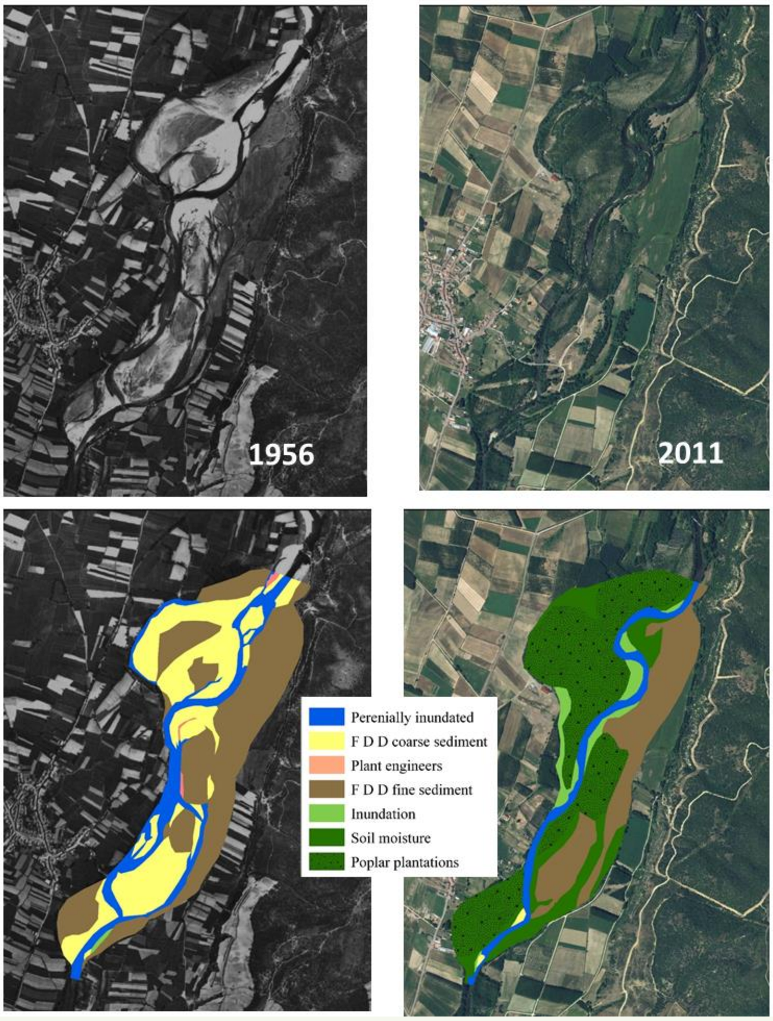


Figure C.4 Identification of functional zones along the riparian corridor and changes over time in the Porma River (NW Spain) (see text and Gurnell et al., 2015 for full functional zones explanation).

Ranges of application

All rivers with distinct riparian corridor (i.e., partly confined or confined segments).

Spatial scale

River segment, Reach.

Frequency of measurement

Once every three years or after significant flood event.

References

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ANNEX D Hydrolomorphological models

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D1. What is a model?

A model is a representation of aspects of reality for a specific purpose. Hence it is not a replica of reality. Models occur in a wide variety, from simple descriptions (word models) to complex three-dimensional computer models. In a general sense, everybody thus uses models. In a more restricted operational sense, however, the term "models" usually refers to mathematical models that run on computers.

D2. Which types of models can be distinguished?

As models occur in a wide variety, it is useful to distinguish different types. The figure below gives an overview.

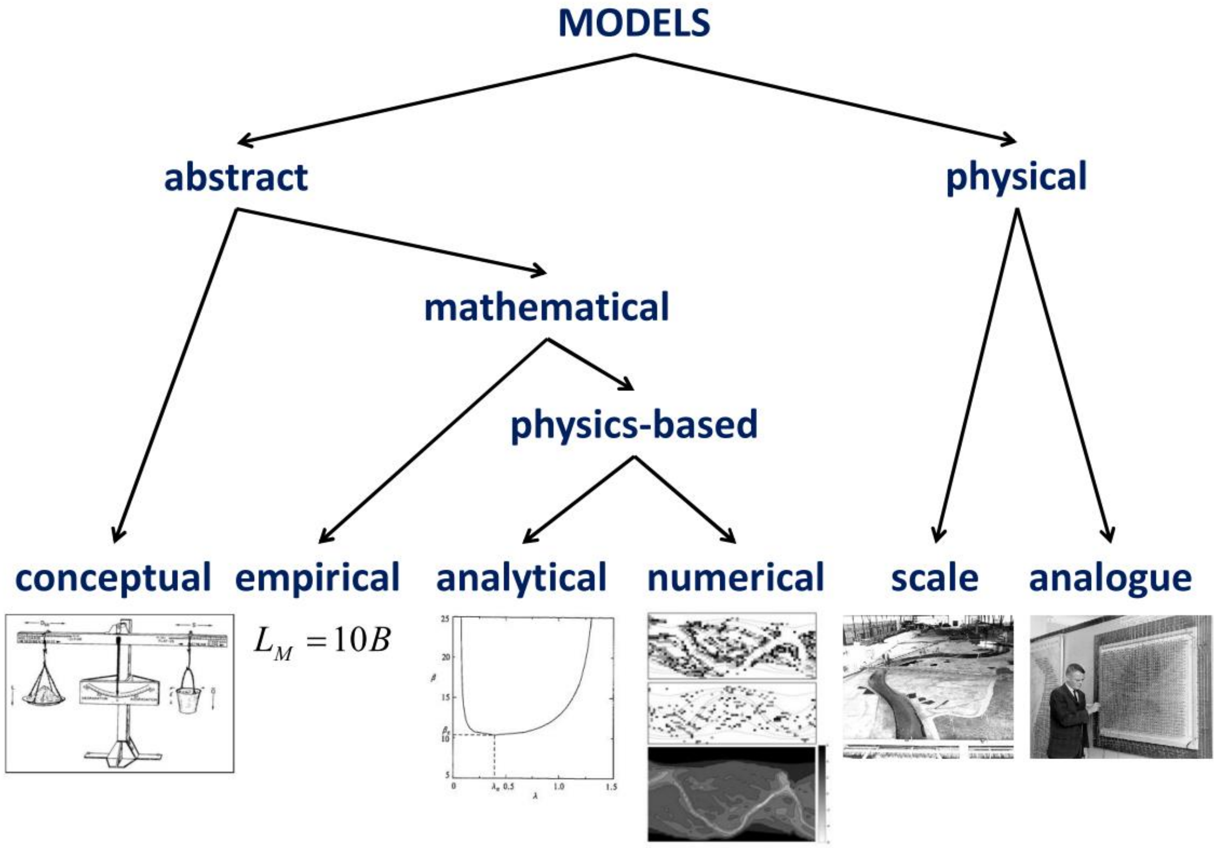

Figure D.1 Summary of different types of models.

Models can be divided into abstract models (models you cannot touch) and physical models (models you can touch). Abstract models can be divided into conceptual models, such as word models and graphical representations, and mathematical models, based on mathematical formulas or equations. Deriving these formulas or equations from data leads to empirical models (induction or data-oriented approach). Deriving them from general principles leads to theoretical models (deduction). The latter are called "physics-based" if general laws of physics are used for the general principles (process-oriented or mechanistic approach). Some controversial models in hydromorphology use non-physics-based principles such as minimum energy dissipation or maximum sediment transport, but those models are not generally accepted.

The equations of mathematical models can be solved in two ways. One way is that they are simplified to an amenable form for analysis. This leads to analytical models. The other way is that they are translated into a form that can be solved by a computer. This leads to numerical models.

Rules of thumb are simple, easy-to-use quantitative models. They are derived from empirical or analytical models.

Physical models can be divided into scale models and analogue models. Scale models are models constructed at a reduced scale, similar to miniature parks. Scale laws and scale rules translate measurements in the model to values in the real world. Analogue models were used in the past, based on analogies between different physical systems. For instance, currents in an electrical circuit are similar to currents in a river network. Amperes and volts in the electrical circuit thus provided information on discharges and water levels in the corresponding river network.

The true picture is nonetheless more complex. Physics-based hydromorphological models include empirical elements too, such as predictors for hydraulic resistance or sediment transport. Empirical models can also result in complex computer models, for instance if they are based on neural networks. The subdivision presented here serves only as general guidance, without including all the subtleties of advanced or hybrid forms.

D3. What is the use of numerical models in river restoration?

The term "models" usually refers to numerical models, based on mathematical equations and running on computers. They can be used for various purposes in river restoration:

- Integration of knowledge on a river in a structured database
- Assessment of a hydromorphological state, enhancing the information from field measurements ("clever interpolation")
- Identification of data requirements for monitoring or measurement campaigns
- Evaluation of the effect of pressures
- Evaluation of the effect of restoration measures
- Evaluation of the effect of scenarios such as scenarios of climate change
- Establishment of design conditions for restoration measures
- Analysis of the sensitivity around tipping points such as the transition between meandering and braiding
- Scientific research and testing of hypotheses, for instance about how hydromorphology interacts with the development of vegetation
- Communication, as a tool for explanation and a basis for discussion

The usefulness of numerical modelling in a particular case depends on the needs to meet these purposes, not on data availability. A lack of data is almost never a valid reason to abstain from modelling.

D4. Who can use numerical models?

The use of numerical models requires background knowledge and training. Staff of river management authorities can feasibly meet these requirements for the simpler numerical models, but usually needs to contract out the application of more complex numerical models. A precise distinction is hard to give. One-dimensional (1D) hydrodynamic models are usually routine tools for management authorities, whereas two-dimensional depth-averaged (2DH) or three-dimensional (3D) morphodynamic models commonly require the involvement of specialized modellers. Most restoration projects do not need 2DH or 3D morphodynamic models. These models are important tools, however, when restoration interferes with navigation.

D5. What is the use of analytical models in river restoration?

One might question the use of analytical models based on simplified equations for physical processes if numerical models are available with a more complete representation of physical processes. However, analytical models provide convenient tools for rapid assessment and rules of thumb. This is the main utility of analytical models in river restoration.

It is worth noting, however, that analytical models are also important for the numerical models used in river restoration. Analytical solutions of mathematical equations are complementary to numerical solutions, as they offer additional insights into the fundamental behaviour of the corresponding physical system. Designing numerical models requires analytical models to determine the appropriate numerical scheme and the type and location of the boundary conditions to be imposed. Analytical models also help the optimization of calibration strategies for numerical models, as they reveal which parameters are responsible for different aspects of the solution. They help the interpretation of results from numerical models as well, because numerical solutions may exhibit spurious wiggles, phase lags or attenuation that in this way can be distinguished from real physical phenomena. Finally, analytical solutions provide exact solutions for certain idealized cases that may serve as validation cases for numerical models.

Table D.1 Comparison of spatial scales for hydromorphological assessment and models.

Hydromorphological assessment		Hydromorphological models		
Name	Indicative space scale	Name (Wright & Crosato, 2011)	Relative space scale	Morphological features
catchment	10^2 – 10^4 km^2	river basin	river basin	sediment yield
landscape unit	10^2 – 10^3 km^2	-	-	-
segment	10 – 100 km	reach	depth divided by slope	longitudinal profile
		corridor	valley width, floodplain width	floodplains, oxbow lakes, meander bends
reach	0.1 – 10 km (>20 widths)	cross-section	main-channel width, active width	bars, channels, pools
geomorphic unit	1 – 100 m (0.1 – 20 widths)	depth	flow depth	bedforms, dunes, scour holes
hydraulic unit	0.1 – 10 m	process	sediment grain size, thickness of viscous sublayer	ripples
river element	0.01 – 0.1 m			

D6. How to deal with different scales?

That models deal with aspects of reality rather than full reality is closely related to scale. On the scale of meander bends and floodplains, models do not represent the details of ripples on the river bed. Ripples are then merely noise represented by averaged quantities such as average bed level and hydraulic resistance (parameterization). On the scale of detailed flow patterns and sediment transport around ripples and dunes on the river bed, the overall picture of the river basin is less important. Influences from far away are captured in the boundary conditions for a local area.

The scale under consideration determines the level of detail and the appropriate modelling approach. For hydromorphological models, scales are defined in another way than for hydromorphological assessment. They are based on relative space scales of morphological features for hydromorphological models, but on partly absolute space scales of areas considered for hydromorphological assessment. As a result, the space scale quoted for the same area and morphological features is smaller for hydromorphological models than for hydromorphological assessment. The table below shows a comparison. Note that the term “reach” refers to different scales in the two systems.

The depth and process scales are realms of scientific research on elementary processes and their interactions. The corridor and cross-section scales are appropriate for analysis of ecosystem degradation, design of river restoration projects, assessment of habitat diversity, and assessment of the sustainability of restoration. The river basin and reach scales are appropriate for analysis of ecosystem degradation and assessment of the sustainability of restoration too, and also for large-scale and long-term impact assessment of restoration.

D7. Which models are presented in the REFORM wiki?

The REFORM wiki contains factsheets of the following hydromorphological models:

- 0D analytical models for flow in compound cross-sections
- 0D analytical models for morphology on long time scales
- 0D sediment budget and routing models
- 1D analytical models for gradually-varied flow
- 1D analytical models for morphology on short time scales
- 1D numerical hydrodynamic models
- 1D numerical morphodynamic models
- 2DH numerical hydrodynamic models
- 2DH numerical morphodynamic models
- 3D numerical hydrodynamic models
- 3D numerical morphodynamic models
- Analytical models for bar patterns and braiding threshold
- Bank dynamics models
- Hydrogeological groundwater-surface water models
- Hydrological rainfall-runoff models
- Numerical meander models
- Soil erosion and sediment yield models

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