European Commission

Criteria for identifying free-flowing river stretches

Common Implementation Strategy for European Union Water Law

Guidance Document No. 41

Version 1 – November 2025

EUROPEAN COMMISSION

Directorate-General for Environment
Directorate C — Zero Pollution, Water Resilience and Green Urban Transition
Unit C.1 — Sustainable Freshwater Management

European Commission
B-1049 Brussels

EUROPEAN COMMISSION

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2025

Manuscript completed in November 2025

1st edition

This technical document has been developed through a collaborative framework (the Common Implementation Strategy for the Water Framework Directive, in the context of its 2025-2027 mandate supporting the implementation of European Union Water Law) involving the Member States, Norway, stakeholder organisations, the European Environment Agency and the European Commission.

The document reflects the informal consensus position on best practice acknowledged by the EU Water Directors. However, the document does not necessarily represent the position of any of the partners. To the extent that the European Commission's services provided input to this technical document, such input does not necessarily reflect the views of the European Commission.

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Luxembourg: Publications Office of the European Union, 2025

PDF ISBN 978-92-68-35098-0 doi:10.2779/6009587 KH-01-25-233-EN-N

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Abstract

Recognizing that restoring freshwater ecosystems and the natural functions of rivers is instrumental in achieving the objectives of the Water Framework Directive, the EU Biodiversity Strategy 2030 includes the target that at least 25 000 km of rivers will be restored into free-flowing rivers by 2030. The Nature Restoration Regulation has translated this target into legal restoration targets, by requiring that Member States (MS) make inventories of artificial barriers to the connectivity of surface waters, remove those which are identified as needing to be removed to contribute to the 25 000 km target (primarily addressing obsolete barriers), improve the natural function of floodplains, and report on their plans and gradual progress towards the free-flowing river target.

In this context, this guidance document outlines criteria for identifying free-flowing rivers by assessing their longitudinal, lateral, and vertical connectivity at local and catchment scale. The aim is to provide a tool to calculate the increase of the length of free-flowing rivers resulting from restoration projects, contributing towards the EU target of restoring 25 000 km of free-flowing rivers by 2030.

Key elements of the approach to identify free-flowing rivers are (1) segmentation of the river into homogeneous reaches; (2) criteria for longitudinal, lateral and vertical connectivity within a homogeneous reach; (3) minimum length criteria to ensure hydromorphological processes and ecological functioning; and (4) a large-scale assessment taking into account sediment connectivity and migration barriers for target fish species.

1 Introduction

A large number of barriers on rivers in Europe has led to a high degree of fragmentation (Belletti et al., 2020), with a major loss of river connectivity resulting in significant changes in hydromorphological processes and biodiversity. In this context, the importance of river restoration and of free-flowing rivers (FFR) has been increasingly recognized by European environmental policy like the European Water Framework Directive (WFD), the European Biodiversity Strategy for 2030 and the European Nature Restoration Regulation (NRR).

The NRR has established for the first time a legal definition of a FFR (Article 3(22)) as a "river or a stretch of river the longitudinal, lateral and vertical connectivity of which is not hindered by artificial structures forming a barrier and the natural functions of which are largely unaffected".

The WFD sets the objective of good ecological status, or good ecological potential, for all water bodies in the EU, on the basis of an assessment of biological, physico-chemical, and hydromorphological quality elements. Among these, several hydromorphological quality elements (Annex V of the WFD) can be associated to one of the three dimensions of connectivity indicated in the legal definition of FFR from the NRR. For example, the WFD quality element "river continuity" mainly pertains to longitudinal connectivity. The WFD quality element "connection to groundwater bodies" mostly relates to vertical connectivity. And the WFD quality element "structure of the riparian zone", as well as "river depth and width variation", are influenced to some extent by lateral connectivity.

As such, restoration of free-flowing conditions of rivers directly contributes to the achievement of the objectives of the WFD. This was recognized in 2020 in section 2.2.7 of the European Biodiversity Strategy for 2030 by setting an EU-level restoration objective of rivers: *efforts are needed to restore freshwater ecosystems and the natural functions of rivers in order to achieve the objectives of the Water Framework Directive. […] To help make this a reality, at least 25 000 km of rivers will be restored into free-flowing rivers by 2030 through the removal of primarily obsolete barriers and the restoration of floodplains and wetlands.*

This objective was later formalized in 2024 through legally binding targets in the NRR, and in particular its article 9. Under this article, MS are required to make an inventory of artificial barriers to the connectivity of surface waters; to identify those barriers which need to be removed to contribute to meeting the objective of restoring 25 000 additional km of free-flowing rivers in the Union by 2030 (in comparison to 2020) and other NRR restoration objectives; and to remove the artificial barriers identified as needing to be removed, primarily addressing obsolete barriers. The NRR refers to obsolete barriers as 'those that are no longer needed for renewable energy generation, inland navigation, water supply, flood protection or other uses'.

Article 9 of the NRR also directly refers to the WFD. The identification of the barriers that need to be removed to contribute to meeting the restoration targets set out in Article 4 of the NRR and fulfilling the objective of restoring at least 25 000 km free-flowing rivers is without prejudice to the WFD, in particular Article 4(3), (5) and (7) thereof. Free-flowing rivers is an objective of the NRR and not of the WFD. This guidance document does not impose any new obligations on Member States under the WFD in relation to river continuity.

To monitor the progress towards achieving the objectives of NRR, including as regards FFR, MS are required to submit a draft national restoration plan (NRP) to the European Commission by 1

September 2026, and then to regularly report on their progress in achieving the objectives of the plan afterwards (cf. NRR articles 16 and 21). According to NRR article 15.3(i), the NRPs shall include, inter alia, the length of FFR planned to be gained by the removal of barriers from 2020 to 2030 and by 2050.

However, given the relatively generic legal definition of FFR provided in the NRR article 3(22), further guidance is needed to ensure that MS report their plans and progress towards NRR objectives in a transparent and comparable way.

Preliminary steps towards such guidance have already been taken, in the framework of the European Biodiversity Strategy for 2030, which set an obligation for the European Commission to provide technical guidance to help MS identify sites for river restoration and help mobilise funding. This led, firstly, to a report initiated by DG Environment in the European Commission, together with the Joint Research Centre, titled “Biodiversity Strategy 2030: barrier removal for river restoration” (European Commission, 2022). This report recognised the need for the definition of free-flowing rivers to be made operational and fit for the European context, to promote river restoration actions. As a consequence, the Free-flowing Rivers Core Group was established under the ECOSTAT working group, with a mandate to develop criteria to assess whether a (stretch of a) river is free-flowing or not. The core group produced an initial technical report presenting such criteria in a report titled “Criteria for identifying free-flowing river stretches for the EU Biodiversity Strategy for 2030” (van de Bund et al., 2024).

This present guidance document, developed by the FFR Core Group and published under the Common Implementation Strategy for EU Water Law, builds upon the report from van de Bund et al. (2024), having reviewed some of its concepts. A pilot phase has shown that it is largely applicable across the European Union.

Additional considerations

In some of the Member States with the highest level of river fragmentation, the implementation of this methodology may be more challenging. Yet, it is clear that in various cases, the application of the key-elements from the methodology is not necessary to determine whether a river is free-flowing or not. In particular, artificial and heavily modified water bodies under the WFD can be assumed to fail reaching free-flowing conditions; and water bodies in high ecological status under the WFD can generally be assumed to reach free-flowing conditions, provided that the assessment under WFD correctly takes into account hydromorphological pressures, consistently with 1.2 of WFD Annex V.

It is worth reminding that, contrarily to the other parts of NRR Article 9 as well as the targets set out in NRR Article 4, which apply at national level, NRR Article 9(1) does not set a country per country target as regards the required length of free-flowing rivers to achieve. This target is to be understood as a target to be achieved jointly by MS at Union level. Therefore, the Commission assessment regarding the contribution to the objective of restoring at least 25 000 km of rivers into free-flowing rivers will be based on the joint information resulting from all the draft national restoration plans submitted by MS, acknowledging that the specificities of Member States may lead to different degrees of achievable progress. The wide use of a harmonized methodology is therefore important to achieve a consistent approach for the EU-wide target. Subsequently, on the basis of the lessons learnt from the initials NRPs, the present guidance document may be updated in the future in preparation of next revisions of NRPs.

Finally, it is underlined that a river or stretch of river is required to pass all four steps, presented therein in a modular way, to achieve the objective of free-flowing river. However, even where FFR condition cannot be achieved, there is a merit in reporting partial progress that have increased the free-flowing characteristics at least compared to some of the local assessment criteria.

On an optional basis, Member States can report on progress in restoring river connectivity even in the cases where free-flowing conditions cannot be achieved, so as to showcase their efforts in river restoration. This will be done through field 9.1.1 of the uniform format of NRPs as defined in implementing regulation (EU) 2025/912. This field 9.1.1 is an optional free-text box where MS can explain their "national approach to meeting restoration targets and fulfilling obligations for the natural connectivity of rivers and *natural* functions of the related floodplains, based on latest scientific evidence".

Details on how this partial progress can be reported in this field will be elaborated at as an addendum to the present guidance document in the beginning of 2026.

2 Basic principles

The methodology described in this guidance document is a stepwise procedure that MS can apply to any river or river stretch to assess whether it qualifies as free-flowing, either under current conditions or following the implementation of barrier removal(s) and/or other restoration measures. Furthermore, it can be applied to show progress in restoring river connectivity and more extensively, for example, to assess the current status of river connectivity at the river basin or at national level.

The concept of river connectivity extends to four dimensions - longitudinal, lateral, vertical and temporal (European Commission, 2022). Following the definition of a free-flowing river given by NRR article 3(22), the presented methodology focuses on the three dimensions most directly affected by physical barriers: longitudinal, lateral and vertical connectivity. If a river is not impacted by any artificial barriers in any of these dimensions, it can be considered to be free-flowing, and no further analyses are needed. Temporal connectivity is partly taken into account by considering ecological flows (European Commission, 2016) in the framework of the assessment of longitudinal connectivity (cf. 3.2.1). Temporary rivers can be included in the assessment, provided that their unimpacted connectivity is properly taken into account, clearly distinguishing natural and human-induced lack of connectivity (Larned et al., 2010).

When the methodology refers to “barriers”, this term is to be understood as artificial physical obstacles, likely to have an impact on river ecosystem connectivity. The main barrier types to be considered, with detailed descriptions of their features and main impacts, are set out in Annex 2 of this guidance document. Geological features (e.g. valley confinement) and natural obstacles (e.g. waterfalls, beaver dams, large wood debris) are not to be considered for removal in the context of the European Biodiversity Strategy for 2030, of the NRR and for this methodology.

The methodology takes into account that river connectivity needs to be considered at different spatial scales. For a river stretch to be free-flowing, it is not sufficient to remove the local barriers to longitudinal, lateral and vertical connectivity within that stretch, but it is also crucial to assess whether the main morphological and ecological functions that a FFR has to maintain are not significantly impacted by up-or downstream barriers elsewhere in the catchment. That is why the assessment procedure consists of a two-tier approach, addressing river connectivity at local and catchment scale, respectively. By assessing the local and large-scale aspects in two separate tiers the method can not only identify current FFR stretches but also points out which barriers need to be removed and which further measures (locally or elsewhere in the catchment) are needed to reach FFR conditions.

Definitions for the key terms that are used are provided in a dedicated chapter at the end of this document (see page 29).

3 Procedure

The assessment procedure is to be applied to river stretches which were identified by the EU MS and that are considered to be or to have the potential to become free-flowing. The procedure is flexible as regards the spatial scale of its application, which enables the user to adjust the criteria to different technical needs, e.g. choosing from a national to local scale, where possible ensuring consistency with existing MS specific approaches and datasets. As an example, some MS may have already prioritised river stretches for restoring connectivity (e.g. based on WFD water body status or based on the broad-scale assessment of longitudinal connectivity as reported in the H2020 AMBER project[1]). This methodology can help establish whether some of these stretches can achieve FFR status.

The procedure consists of a two-tier approach consisting of local and large-scale assessments (Figure 1). A river must fulfil both the local and large-scale criteria to be considered a free-flowing river (FFR).

Local assessment

- Step 1 – Identification of homogenous river reaches (HR) within the potential FFR stretches.
- Step 2 – Homogeneous reach assessment addressing the barriers to connectivity within each homogeneous reach. This requires reliable information on the presence of barriers. If existing barrier inventories are used, it may be necessary to verify this information in situ to ensure that it is up to date.
    - Addressing longitudinal connectivity
    - Addressing lateral connectivity
    - Addressing vertical connectivity
- Step 3 – Minimum length of potential FFR stretch, verifying whether the (potential) FFR stretch has sufficient length for the typical ecological and hydromorphological processes to take place.

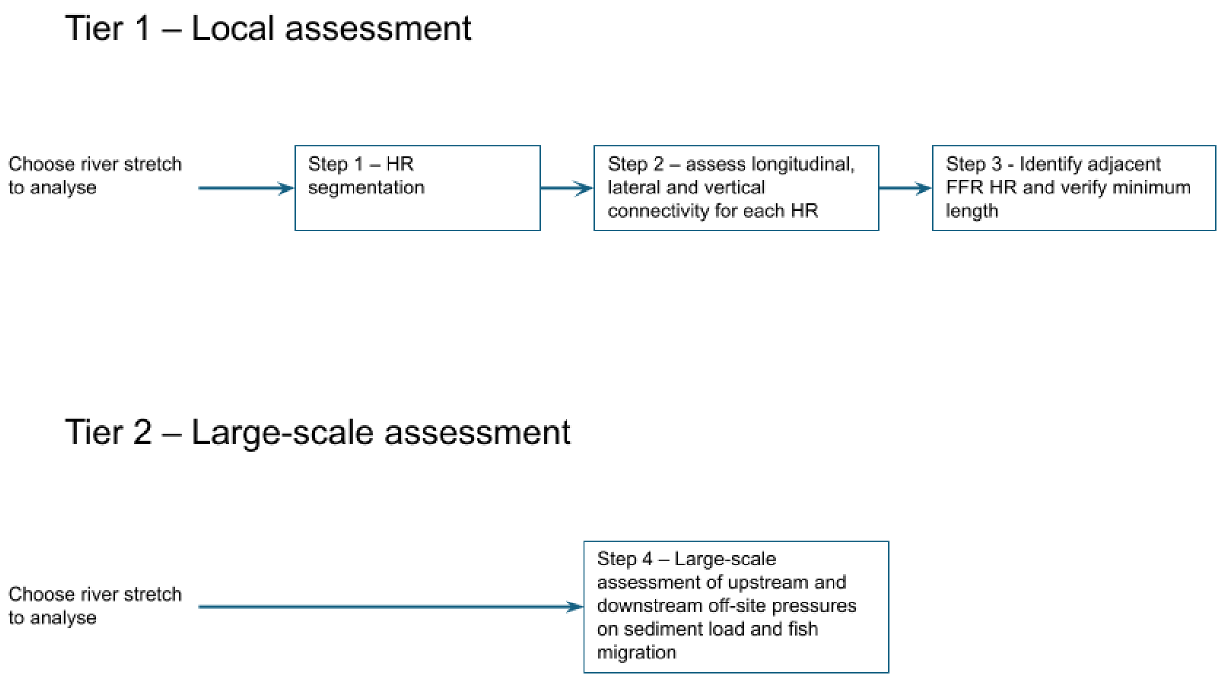
Large-scale assessment

- Step 4 – Large-scale assessment of upstream and downstream pressures on potential FFR stretch, addressing the limitations to continuity outside the (potential) FFR stretch (consisting of one or more homogeneous reaches) do not significantly hinder morphological and ecological functions within that stretch.

The local and large-scale assessments can be carried out independently, but both need to be considered before concluding that a river stretch is free-flowing.

[1] https://amber.international

Figure 1 - Schematic overview of the different elements of the procedure to evaluate whether a river stretch fulfils the criteria to be a FFR. A river stretch must fulfil both the local and large-scale criteria to be considered a FFR



Particular cases and minimization of the administrative burden

In order to ensure a minimization of the administrative burden, it is important to precise that :

- Artificial and heavily modified water bodies designated under WFD article 4(3) are such that the changes to the hydromorphological characteristics of that body which would be necessary for achieving good ecological status would have significant adverse effects on various water uses or the wider environment. As a result, if the conditions of Article 4.3 are met, it can be assumed that this water body does not fulfil the criteria for a free-flowing river and it is not necessary to apply the methodology of this guidance to demonstrate this (except in cases where the Member State has the intention to designate this water body as a natural water body instead of an artificial or heavily modified water body in a next river basin management plan under the WFD).

- On the opposite, a river can generally be considered free-flowing if it has been assessed as having high ecological status in the framework of WFD[2]. This is because at high ecological status according to Annex V of the WFD, there is "no, or only very minor, anthropogenic alterations to the values of the physico-chemical and hydromorphological quality elements for the surface water body type from those normally associated with that type under undisturbed conditions." In this case, provided that the national assessment methodologies used under WFD sufficiently take into account hydromorphological pressures, it is not necessary to apply the methodology of this guidance to demonstrate that the water body is a free-flowing river.

3.1 Step 1 – Identify homogeneous river reaches

The first step of the procedure aims at identifying the **homogeneous reaches (HRs)** within the river stretch chosen for the analysis, on which Step 2 will be applied. The key requirement for a HR is that it allows to apply the methods in Step 2 in a coherent way. Within a HR, conditions should be sufficiently uniform (i.e. with no significant changes in natural confinement, slope, imposed flow and sediment load; see Brierley and Fryirs, 2013; Gurnell et al., 2014; Rinaldi et al., 2016; Malavoi & Bravard, 2010). Such conditions determine a homogeneous channel morphology and, consequently, a typical assemblage of geomorphic units, thus of riverine habitats.

The length of HRs may vary and usually it is equal to 10 - 100 times the average bankfull width of the river stretch.

For the purpose of this procedure, the minimum characteristics to be considered to identify a HR are the following:

— a HR needs to belong to one single river type: single-thread (straight, sinuous, or meandering); transitional (also defined as wandering); multi-thread (braided or anabranching). See Annex 1.

— there should be no change in the natural confinement of the HR (e.g. confined, partly confined, and unconfined).

— there should be no permanent major natural barriers (e.g. lakes, waterfalls) within a HR

[2] The reverse does not necessarily hold true. A river may be considered free-flowing on the basis of its hydromorphological characteristics, but may not be assessed as having high ecological status under the WFD due to, for example, chemical and physico-chemical pollution.

— there should be no major change in the average bankfull width, slope and/or discharge within a HR.

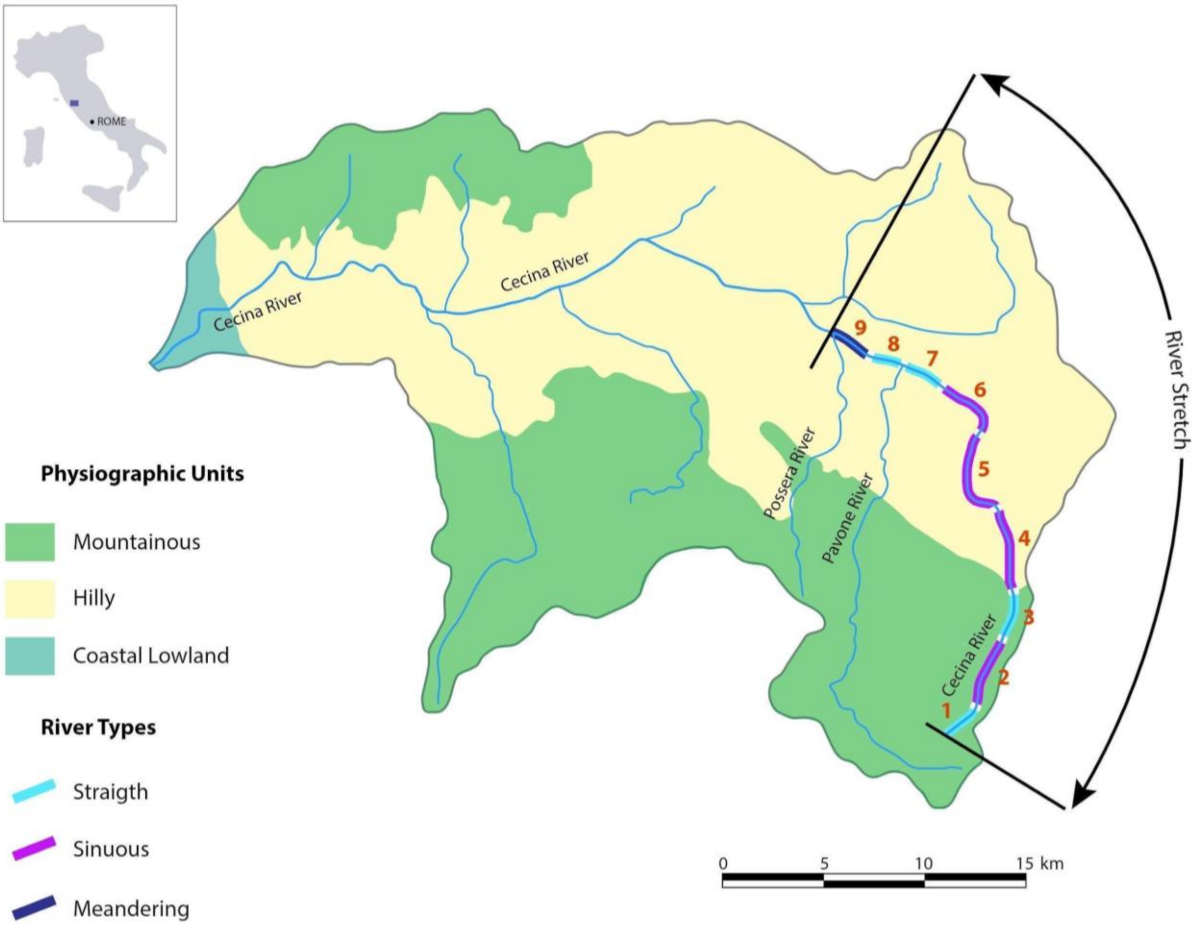
— the HR should be homogeneous regarding the reference fish community.

Segmentation of a river stretch into equal distance portions usually does not fulfil these criteria and may result in incorrect assessments through the procedure.

There are several possible methods to identify homogeneous reaches. Some MS have already segmented their rivers using, for example, their WFD hydromorphology assessment methodology (i.e. ISPRA, 2016; CEN, 2020; Gurnell & Grabowski, 2020) and may simply use these as HR as long as they fulfil the minimum characteristics specified above.

Besides the above characteristics, it should be kept in mind that confluences do not necessarily have to be absent from a homogeneous reach, but it is important to remember that confluences, depending on their size (and discharge), may have an impact on the size of a downstream section, requiring a segmentation into two different reaches.

Figure 2 - Segmentation of the Cecina River stretch into nine homogeneous reaches. The Cecina River catchment is located in Tuscany, Italy



(source: modified from ISPRA, 2016).

Figure 2 shows an example of the segmentation of a river stretch into HRs. The example considers a stretch of the Cecina River in Italy which goes from the spring to the confluence with the Possera River. The distinction between the HRs 1, 2 and 3 is dictated by a change in the confinement in the mountainous region as well as a change in the river type (from straight to sinuous, see Annex 1). The

HRs 4, 5 and 6, despite having the same river type, show an abrupt change in the river confinement in the hilly region that provokes a change in the average bankfull width. Between the homogeneous sections 6 and 7, there is a change in the river type (from sinuous to straight), while the presence of the confluence of a major tributary, i.e. the Pavone River, delimits the HRs 7 and 8. Finally, the HRs 8 and 9 are identified by another change in the river type (from straight to meandering).

3.2 Step 2 – Homogeneous reach assessment

This part of the procedure aims to verify whether the longitudinal, lateral and vertical connectivity within the identified HR is ensured.

3.2.1 Step 2a – Addressing longitudinal connectivity

The longitudinal connectivity of riverine systems allows the upstream and downstream movement of biota, as well as the flow of energy and the transfer of matter, such as water, sediments and nutrients, from upstream to downstream stretches. This facilitates and ensures the existence of a mosaic of riverine habitats connected to each other across the basins. When longitudinal connectivity is disrupted, those flows and matter transfers will be directly impacted. The loss of longitudinal connectivity may have significant impacts on habitat diversity, aquatic communities (e.g. fish, macroinvertebrates, plants), water and sediment quality as well as sediment composition.

The analysis consists of three distinct checks:

— **Fish mobility check**. If, in the reference conditions, a fish community is expected to be present, the absence of barriers that have an impact on fish mobility within the HR needs to be verified and confirmed.

Any artificial structure that is passable in both directions (both from downstream and from upstream) in an unaided way by all species in the reference fish community is not considered as a barrier (see barrier types overview in Annex 2 or other proven procedures, as in Makomaska-Juchiewicz & Baran 2012; Baudoin et al., 2014; Kreutzenberger et al., 2020; Nielsen & Szabo-Meszaros 2022). Dams with artificial fish passages do in the large majority of cases not fulfill these criteria. A river type specific passable ramp could be an example fulfilling these criteria. For the purpose of this methodology it is acceptable that the barrier is not passable in very low flow conditions, as far as it can be demonstrated that this does not significantly affect populations of the reference species.

In some cases, especially in steep mountain streams, temporary rivers, or as a result of other natural barriers and disturbances, fish communities may be naturally absent. In such situations, the fish mobility check can be excluded from the assessment.

Information regarding the reference fish community in the HR under consideration can be acquired from the WFD fish reference conditions for the applicable river types, through previous plans, studies and reports concerning the river itself or from scientific literature. If such sources are not available, estimation of the reference fish community should be conducted based on the expert opinion, e.g. using data on the fish communities from similar river stretches.

— **Sediment transport check**. This is to verify and confirm the absence of barriers within the HR that significantly alter sediment transport.

To perform this check, the users can refer to consolidated procedures set out in the relevant literature (e.g. the Morphological Quality Index (MQI) methodology, see Rinaldi et al., 2016; MIMAS, see SEPA, 2012; Valmorph, see Rosenzweig et al., 2012). In Annex 2, there are indications of barrier types that may be considered negligible in obstructing sediment transport. However, it is always advisable to verify in place and develop a specific study.

— **Ecological flow and hydrological alteration check**. This is to ensure that an ecological flow (European Commission, 2016) is guaranteed during the whole year in the HR. In particular, it is important to verify that hydrological alterations do not result in non-natural physical disconnections within the HR, impacting the mobility of fish and/or sediments (e.g., linked to local interruption of surface flows or hydropeaking).

Once the above analysis is carried out, and if all the relevant checks are successfully passed, the HR is considered to fulfil the free-flowing criterion for longitudinal connectivity.

3.2.2 Step 2b – Addressing lateral connectivity

This step consists of an incision check (making sure that there is no permanent disconnection to the floodplain) followed by a lateral connectivity check based on an evaluation of the impact of artificial barriers within an assessment corridor on the lateral connectivity of the HR.

Incision check

Some river reaches have strongly incised riverbeds, due to gravel extraction and/or anthropogenic upstream pressures inducing sediment deficit, and, consequently, they are permanently disconnected from their former floodplains (e.g. flooded only with Q_{50} or higher). Such reaches cannot be defined as FFR, even in the absence of artificial lateral barriers, as the key processes linked to lateral connectivity are impaired. Therefore, it has to be assessed first whether the reach falls within this category. If so, no further analysis on lateral connectivity is necessary and the procedure stops. Otherwise (including the very common situation when the river channel has some degree of incision, but is not fully disconnected from the alluvial plain), the lateral connectivity should be further evaluated as described below.

Lateral connectivity check

Box 1. Overview of abbreviations used in Step 2

L_c: Length of the homogeneous reach assessed.

L_{tot}: total barrier length, meaning the sum of the lengths of all lateral barriers (attached and non-attached to the riverbanks) located in the assessment corridor

L_{att}: sum of the lengths of attached lateral barriers located in the assessment corridor

C: width of the assessment corridor (starting from each riverbank) where lateral connectivity assessment is taking place. $C = pW$

p: multiplying factor used to compute the width of the assessment corridor (C) where lateral connectivity assessment is taking place. It takes different values depending on the river type, as shown in the section 'Identification of the assessment corridor'.

W : average bankfull width (averaged over the length of the HR)

Identification of the assessment corridor

In order to assess the lateral connectivity of the HR under consideration, it is necessary to identify an assessment corridor, meaning an area adjacent to the river channel delimiting the minimum portion of land where the river should be allowed to freely erode, deposit, and flood, following its dynamic evolution.

The width of the corridor naturally subject to river processes is governed by many factors, including valley landforms, surface geology, and the length and slope of the river channel. Using the whole corridor/floodplain for the FFR assessment is clearly not feasible, due to the presence of urbanisation and infrastructure. This would exclude practically all non-confined rivers from being assessed as FFR. Here, a simplified procedure for delimiting a smaller corridor, for the sole purpose of this assessment procedure, is proposed.

The starting point is to determine the average bankfull width W within the HR (see Figure 3). The assessment corridor is delineated by multiplying W by a factor p, which depends on the river type (Brierley & Fryirs, 2013). The distinction between single-thread, transitional, braided and anabranching river types (see Annex 1) should be made according to consolidated procedures (Gurnell et al. 2014, ISPRA 2016, Rinaldi et al. 2016).

The following *p* values were chosen:

— $p = 2$ for single-thread rivers

— $p = 1$ for transitional rivers;

— $p = 0.5$ for anabranching rivers;

— $p = 0.1$ for braided rivers.

The bankfull width W to use in this computation is the average value in the homogeneous reach, under the current conditions. To determine it, W can be evaluated in some cross-sections (e.g. in 10 equally spaced cross-sections) and then the average value represents the current bankfull width for the HR under investigation. Alternatively, the bankfull area can be divided by the reach length. It is important to note that braiding morphologies occur and self-maintain as long as sediment dynamics is not significantly impaired, otherwise they tend to degrade to simpler morphologies. Therefore, in the case of braiding rivers, for the purpose of this evaluation, it is assumed that the river corridor can be considered as almost coincident with the bankfull width itself, i.e. imposing a low $p$value.

Figure 3 clarifies the concept of bankfull width, and Figure 4 helps in defining the bankfull width for different river types, namely single-thread (straight, sinuous, meandering) and multi-thread (braided and anabranching). For the transitional type (wandering), the presence of fluvial bars or islands must be addressed in the same way as for braided or anabranching rivers.

Thus, the formula for the identification of the fluvial corridor width C is $C = pW$ and must be applied on each side of the river (starting from the riverbank). In other words, once the line of each riverbank has been identified, the river corridor extends from the riverbank line outward of the river by a value equal to C. In this way, we generate a buffer around the two riverbanks that identifies the fluvial corridor, within which the lateral connectivity will be assessed (Figure 5, top left panel).

It is also possible to draw the corridor from the centerline of the river, rather than from the riverbanks (*centerline approach*). If so, the formula becomes: $C = pW + 0.5W$ (to be applied on each side of the centerline). However, the centerline approach is not recommended when the banks are very diverse as it can lead to the exclusion of some important habitats within a reach (which is typical e.g. for meandering alluvial rivers).

In very complex situations this approach can be adapted taking into account the whole floodplain for the delineation of the fluvial corridor.

Figure 3 - Illustration of the bankfull width concept defined as lateral extension of the free water surface perpendicular to the river flow direction when the water completely fills the cross-sectional river active channel up to the floodplain or a terrace or hillslope (for further details see the Definitions section)

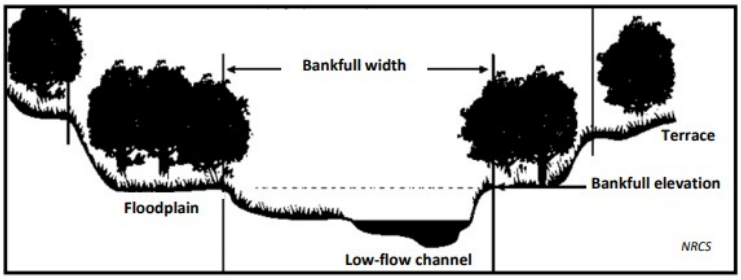
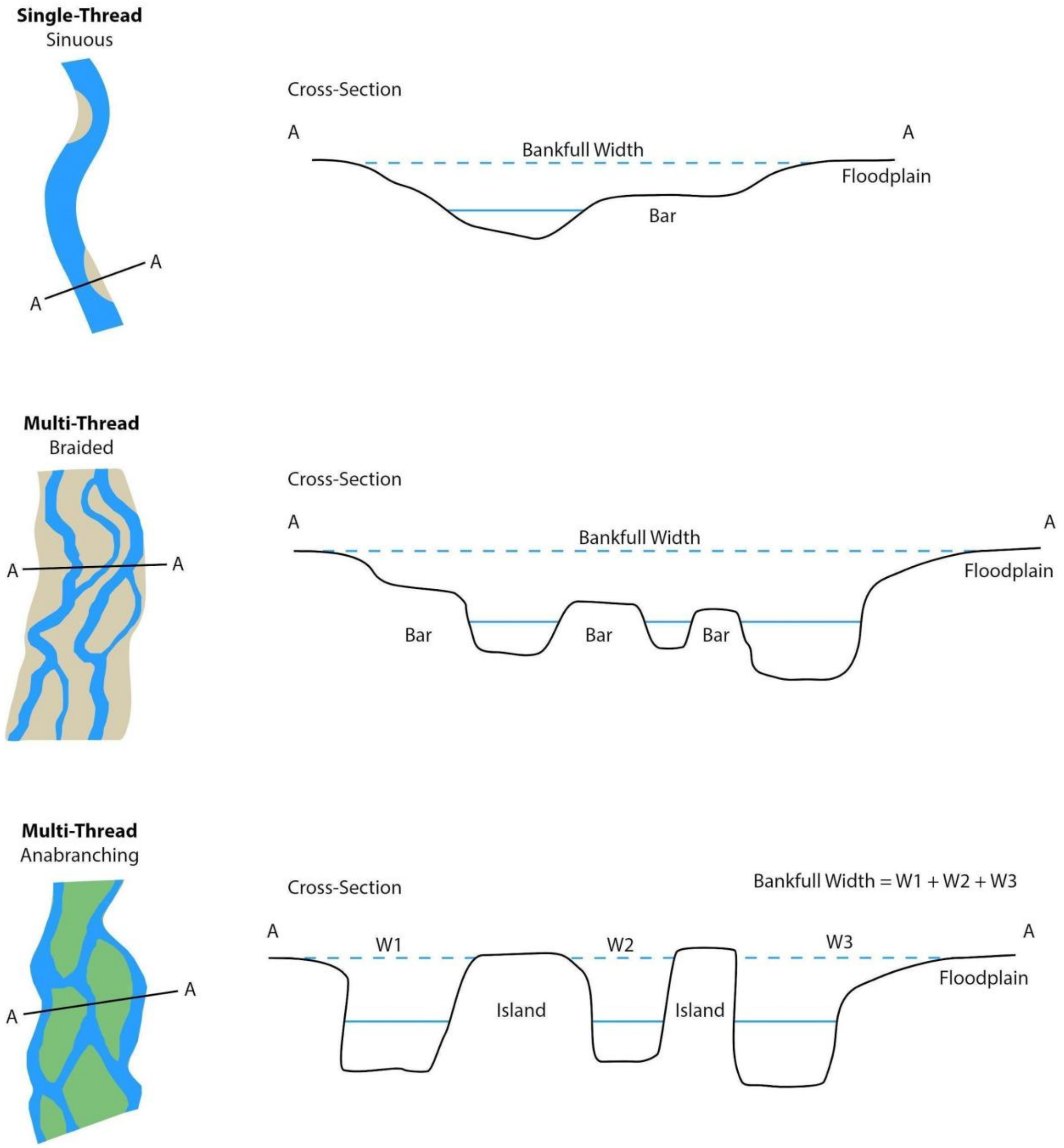


Figure 4 - Identification of the bankfull width in different river types. The water surface refers to low-flow conditions (continuous light blue line on the Cross-Section drawing below) or bankfull conditions (dashed light blue line on the Cross-Section drawing below).



Identifying and mapping the barriers to lateral connectivity

Once the river corridor for the homogeneous reach under consideration has been identified, the lateral barriers within this corridor must be identified and mapped. Lateral barriers are both those preventing flooding (e.g. levees/embankments, see Annex 2) and those preventing erosion/lateral mobility (e.g. bank protections; groynes, see Annex 2) located inside the fluvial corridor. If information on lateral barriers is *a priori* not available, some reliable proxies can be used, such as:

— The presence of residential settlements, roads or railroad tracks is usually associated with some type of bank protection.

— Flood maps corresponding to different return periods (e.g. 10- and 100-years) can be used to highlight the presence of levees, embankments or, conversely, natural confinement (that is not considered as a limitation of connectivity). For instance, if a 10-year flood map and a 100-year flood map coincide, it may be due to the presence of a levee.

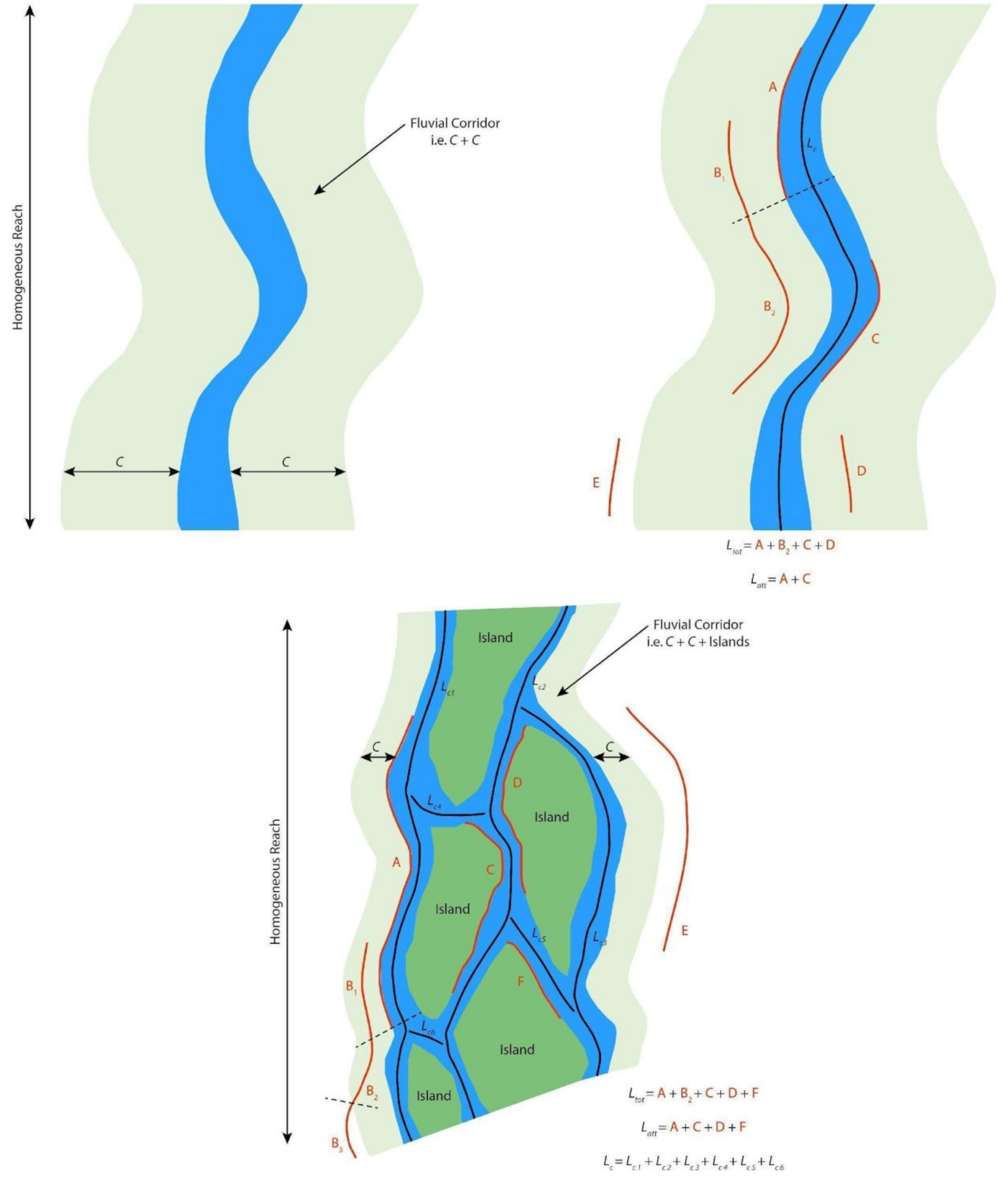
Calculating the cumulative length of the lateral barriers (total and attached)

Subsequently, the cumulative length L_{tot} must be computed considering all the lateral barriers (from both sides of the river) in the homogeneous reach that fall within the fluvial corridor (Figure 5). If two barriers on the same side overlap (e.g. presence of an attached bank defence and of a more distant embankment), the length they have in common is taken into account only once.

Additionally, the cumulative length of only lateral barriers directly attached to the riverbanks L_{att}, i.e. the bank protection structures that in some way substitute the natural riverbanks or the levees that are closely in contact with the banks, must be separately evaluated, as their impact on lateral connectivity is higher. These lateral barriers are directly in contact with the flow and consist of riverbank protection works (walls, riprap, gabions, groynes) or levees/embankments. Also, for the computation of L_{att}, we consider the lateral barriers present on both sides of the river. In case of groynes protecting riverbanks from erosion, the length to be computed is not that of the groynes themselves, but the extension of the riverbank where erosion is hindered by the presence of the groynes.

For anabranching rivers, the evaluation on the presence of lateral barriers must be done considering each single channel.

Figure 5 - Identification of the fluvial corridor and deriving the length of the homogeneous reach (L_c), the total length of the lateral barriers (L_{tot}), and the total length of the attached lateral barriers (L_{att}) for different river types.



Determining lateral FFR conditions based on barrier length compared to HR length

Once L_{tot} and L_{att} are obtained, they are compared with the length L_c of the homogeneous river reach. For anabranching rivers, the length L_c is equal to the sum of the length of each single channel. For semi-confined river reaches, the bank extension which is directly in contact with the valley slopes is excluded from this computation (both in relation to the extension of barriers, if any, and to reach length).

Hence, for all the river types except for meandering, the condition to be free-flowing is obtained only if both the following conditions are satisfied:

— $L_{tot} < 0.4L_c$ considering all the lateral barriers present in the fluvial corridor;

— $L_{att} < 0.2L_c$ considering only the lateral barriers that are attached to the riverbanks.

For meandering rivers, for which just stopping erosion along the outer bends is enough to stop mobility, the thresholds need to be stricter:

— $L_{tot} < 0.2L_c$considering all the lateral barriers present in the fluvial corridor;

— $L_{att} < 0.1L_c$ considering only the lateral barriers that are attached to the riverbanks.

Box 2. Summary overview of Step 2b

This summary is to give an overview of the methodology in Step 2b. Specific requirements in the text need to be taken into account for a correct assessment.

— Check if the reach is affected by strong riverbed incision determining permanent disconnection from the former floodplain

— Define the average bankfull width W within the homogenous reach (see Figure 3-4)

— Measure total length of the homogenous reach L_c

— Choose the multiplication factor p according to the given river type

— Define a fluvial corridor C by the use of W (bankfull width) and p (multiplying factor); Use one out of two options (see Figure 5):
 - Define C by starting by each river bank: C = Wp
 - Define C by starting from the centreline of the river: C = Wp + 0.5W

— Determine and map all barriers to lateral connectivity within C

— Compute L_{tot} within C (take into account overlapping barriers only once)

— Compute L_{att} within C (take into account overlapping barriers only once)

— Check on FFR – thresholds: $L_{tot} < 0.4L_c$; $L_{att} < 0.2L_c$

— Check on FFR – thresholds: for a meandering river only $L_{tot} < 0.2L_c$; $L_{att} < 0.1L_c$

3.2.3 Step 2c - Addressing vertical connectivity

This step is designed to implement a simplified assessment to identify the most evident cases where vertical connectivity is compromised.

Vertical connectivity should be addressed with regard to the morphology and geology of the reach and the evidence of exchange between the surface water and the groundwater. Depending on these circumstances, the presence of riverbed sills or other paved barriers within the reach will be more or less relevant, acting as an insignificant or aggravating factor. When this information is not available, the criterion could be that the presence of stone/concrete paving is allowed for a limited length of the HR, specifically less than 5% of the length Lc of the HR. This ensures that their presence minimally affects vertical connectivity and riverbed composition (Rinaldi et al., 2016). In some circumstances, the presence of cumbersome fords present in the same HR can produce the same effects as paving. It is therefore necessary to estimate the extension of these structures within the same HR, obtain the total extension and evaluate if it is less than 5% of the HR length. Remote sensing images are typically reliable for identification, except for small, confined rivers where identifying consolidation structures may be challenging. In such instances, consult the national cadastre of hydraulic works, if available, refer to pre-existing studies, or implement ad-hoc surveys.

In case that the extension of ford or paving structures exceeds 5% of Lc, then the HR cannot be considered free flowing.

3.3 Step 3 – Minimum length of free-flowing rivers

Once the procedure in Step 2 has been carried out for all the homogeneous reaches, if the conditions to be free-flowing are satisfied, an additional check is needed, in order to verify whether their length is sufficient to ensure that it can support the development of typical morphological patterns, and associated habitats. The length of a river stretch identified as potentially free-flowing in the previous steps is thus compared to a minimum length threshold. If the procedure has identified adjacent potentially free-flowing HRs, their length is summed up and used for such comparison. When summing up the length of contiguous potentially free-flowing HRs, only HRs in a single river stretch are considered.

As previously discussed, the concept of free-flowing rivers implies that sufficient space is ensured for the development of typical fluvial processes. In relation to morphological ones, considered here, in order to be identified as free-flowing, a river stretch needs to ensure connectivity for a sufficient length to allow the development of the morphological patterns typical for the specific river type (e.g.,: gravel bars, meanders, etc.). Morphological patterns and associated structures exhibit a certain regularity and scale that correlates with the width of the channel. Their distance can be predicted by empirical formulae coming from the observation of a great number of rivers and/or theoretical approaches (e.g. Yalin, 1992; Hundey & Ashmore, 2009; Leopold & Wohlman, 1960, Ragno et al., 2022). The minimum length for FFR can thus be set, according to the river type and the average bankfull width, ensuring a minimum number of repetitions of the expected morphological pattern. Similar approaches underpin river morphological segmentation for morphological evaluation and classification. For instance, Gurnell et al. (2014) suggest that, "as a general rule, the length of a reach should not be smaller than 20 times the mean channel width, although shorter reaches can be defined where local circumstances are particularly complex".

The proposed approach is mainly based on the following empirical relationships:

For **(sinuous) single channel rivers**, Yalin (1992) derived theoretically that the length L between successive alternating bars is approximately 6 times the channel width:

$$L=6W$$

For **braided rivers**, Hundrey and Ashmore (2009) derived an empirical estimate for the confluence-bifurcation length L of approximately 5 times the channel width:

$$L=5.09W^{0.97}$$

For **anabranching rivers**, Ragno et al (2022) derived a "quasi-universal" empirical relationship between the length of a single anabranch "loop" (distance between a channel bifurcation and its subsequent reconnection) and the upstream average channel width:

$$L \approx 8 \div 13W$$ (with lower values for sand-bed rivers and higher for gravel-bed rivers)

For **meandering rivers**, the meander wavelength L* can be predicted by (Leopold & Wohlman, 1960):

$$L^* = 10.9W^{1.01}$$

assuming that the river length (along the thalweg) L scales approximately with sinuosity P, the distance between two meanders becomes:

$$L \approx 10.9\ P\ W^{1.01}$$

and assuming an average sinuosity equal to 2 for meandering rivers, this leads to:

$$L = 21.8W^{1.01}$$

Amplifying the results of the above equations by a factor of 50 (in order to have on average 50 repetitions of the morphological patterns enabling the formation of sufficiently extensive fluvial habitats), with the exception of braided rivers, for which this value is set to 15 (to take account the different effect on habitats of the specific pattern considered), assuming that for transitional (wandering) rivers the same relationship as for braided rivers applies, considering the lower end of the range of L for anabranching rivers, and approximating to linear relationships between L and W the above equations, the following "minimum length" relationships are defined:

For **(sinuous) single channel rivers**: L=300W

For **braided and wandering rivers**: L=250W

For **anabranching rivers**: L=400W

For **meandering rivers**: L=330W

These type-specific relationships are further adapted as follows:

- the lower threshold is set to 3000 m (considered as a minimum target for connectivity restoration actions, taking into account the current level of fragmentation of European rivers);
- the upper threshold is set to 15000 m, as:

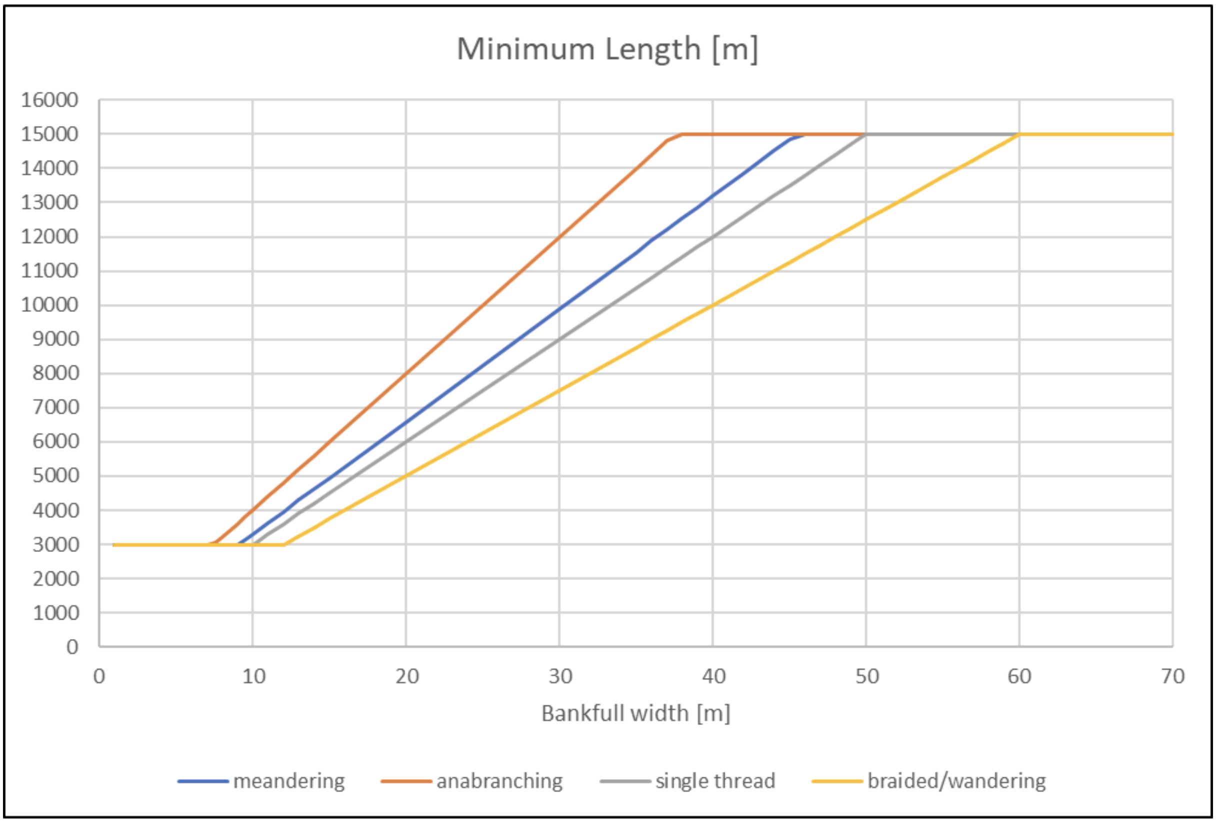
  i) for wider rivers the transversal distribution of fluvial habitats ensure sufficient extension/heterogeneity even for lower channel lengths;

  ii) very high minimum lengths would not be realistic and thus miss the main purpose of the FRR concept introduction, i.e. to foster/accelerate restoration of connectivity.

This leads to the minimum length relationships illustrated in Figure 6

Finally, in cases where the total river length is less than the minimum length as defined above (as it may be the case for some very small streams or for rivers between two lakes), if the whole river is free-flowing the minimum length condition is assumed to be fulfilled.

Figure 6 – Type specific minimum lengths applying the recommended threshold values and relationships between bankfull width and minimum length



4 Large-scale assessment

In addition to the examination of the lateral, longitudinal and vertical connectivity of the HRs within a river stretch, it is necessary to assess whether the main morphological and ecological functions that a FFR has to maintain are not significantly impacted by barriers upstream or downstream of the river stretch.

This large-scale assessment can also be carried out independently from the previous steps, for example, as part of an initial screening exercise identifying candidate FFR stretches.

The methodology focuses on two major alterations: sediment load from upstream and mobility of fish. For instance, a river stretch could have no or negligible local pressures, yet its hydromorphological and ecological functions could be impaired by a major reduction of the sediment load due to upstream barriers. Moreover, barriers can isolate the river stretch under investigation, preventing the migration to or from the reach of fish species that are part of the reference community.

4.1 Sediment load: Upstream off-site pressures

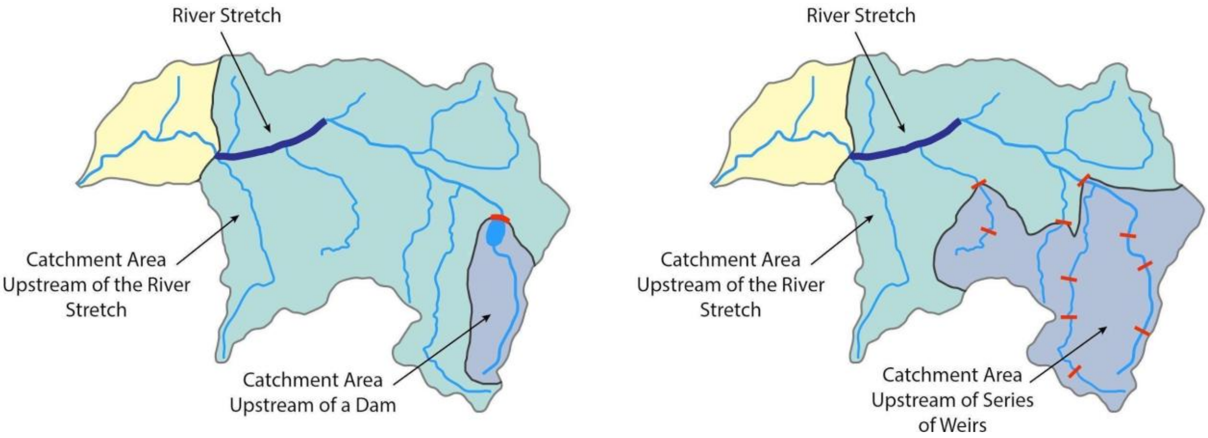
To understand if the river stretch under investigation is affected by a sediment deficit resulting from a blocked sediment transport, an analysis should be carried out focusing on the following steps:

1. Confirm whether there are barriers upstream the river stretch that could significantly reduce the sediment transport and connectivity downstream. If there are no barriers or only barriers that have no significant impact on sediments (based on barrier type, see Annex 2), the upstream continuity can be considered fulfilled. Conversely, if there is at least one such barrier in the upstream catchment, an assessment of its effects is necessary, as described below.

2. Assess whether the geomorphological behaviour of the HRs within the river stretch has been altered resulting in relevant morphological alterations (e.g. change of morphological configuration, ongoing channel narrowing/incision or significant alteration of sediment granulometry), taking into account the mitigation measures that are implemented at the upstream barriers. If it can be demonstrated that the upstream barriers have a negligible effect, the upstream continuity can be considered fulfilled. Conversely, if there are significant alterations due to these barriers, the upstream continuity is not fulfilled, thus the reach cannot be assessed as free-flowing.

The above analysis should be based on the best available knowledge and the latest scientific evidence, whether from studies or local expert knowledge. The CIS document "Integrated sediment management – Guidelines and good practices in the context of the Water Framework Directive (European Commission 2021) provides important background information on this issue. If no detailed geomorphological studies are available, the adoption of suitable proxies becomes necessary to assess the upstream pressure. When reliable estimates are available of the fraction of the bedload that is intercepted by upstream reservoirs, retention weirs or other relevant barriers, it can be considered that if **less than 30%** of the load is stopped, the condition on upstream continuity is sufficiently fulfilled. If such data is not available, the suggested proxy is the percentage of the upstream catchment surface intercepted by relevant barriers (Figure 7; ISPRA 2016; Rinaldi et al., 2016)). If the existing barriers having a relevant effect on sediment transport (such as dams and retention weirs) intercept **less than 30%** of the catchment surface area upstream of the river stretch calculated starting from the lower end of the river stretch (see Figure 7, left panel), the condition on upstream continuity is considered fulfilled. If on a given upstream stretch there are more barriers in series, the catchment area intercepted must be calculated only in relation to the most downstream one (see Figure 7, right panel).

Figure 7 - Example of how to consider and compute the severity of barriers' sediment load interception in the case of a dam (left) and of a series of weirs (right)



(source: modified from ISPRA, 2016).

In the case of natural lakes or other natural upstream sediment barriers, the catchment area drained by the lake should not be considered in the calculation, as the corresponding sediment interception is not considered as an alteration.

4.2 Fish migration: Downstream off-site pressures

As a general principle, there should be no artificial downstream migration barriers for the fish taxa representing the reference communities in the candidate river stretch, considering the migration type (diadromous, potamodromous) and the migration distance (short, medium, and long) of the fish species. Further guidance on defining the reference communities can be found in Chapter 3.2.1.

If there are diadromous or long-distance migrating potamodromous species in the reference community of the candidate river stretch, the general rule to be free-flowing is that all relevant downstream barriers should be mitigated by functional fish passage facilities, so that all species in the reference community have access to the FFR. For potamodromous species relevant barriers are all barriers within the migratory distance of the reference fish community. Conceptually, access to habitat necessary to accommodate biological functions such as spawning needs to be maintained. This may include sufficient access to relevant tributaries, which serve as spawning grounds. The necessary range can be determined with the help of fish biological studies or expert opinion. For artificial barriers that may be considered passable despite lacking dedicated fish passage facilities, several factors must be evaluated. These include the barrier's construction characteristics, such as slope, material, and surface texture, as well as water depth both beneath and flowing over the barrier, as well as flow velocity. These physical conditions must be considered together with fish species migration demands and their availability to overcome obstacles. Expert opinion from a fish biologist and/or a specialist in ecohydraulics relying on existing tools or methods (see box 3) may be necessary to make an informed judgment.

However, some exceptions to this rule should be allowed to keep the FFR concept achievable. As a general principle, if there are heavily modified water bodies downstream, only those mitigation measures that the WFD requires for the achievement of good ecological potential with regards to fish migration under the Water Framework Directive are needed. Detailed guidance on this can be found in CIS guidance No. 37 (EC, 2019). Such exceptions include the following:

1 where, for the time being, it is not technically possible to mitigate at least one of the barriers downstream;

2 when mitigation of at least one of the downstream barriers would significantly affect the use of a heavily modified water body (extremely unlikely for fish passage measures);

3 when the mitigation of at least one of the barriers downstream would have prevailing negative impacts on the wider environment (for example, foster the spreading of invasive species);

4 when the mitigation of at least one of the barriers downstream would not bring any significant ecological benefit (for example, if there are already many fish passes in a row with a combined efficiency close to zero, building more fish passes would not be useful).

Box 3. Examples of tools that can be used to support the expert judgment for the large-scale fish migration check

Fish Community Habitat Types - A concept of Fish Community Macrohabitat Type (Parasiewicz et al 2023) can be used to determine functional habitat unit, i.e. the river length utilized by metacommunity occupying one macrohabitat type.

Population connectivity - a Population Connectivity Index sensu Angulo-Rodeles et al (2021) could be implemented to estimate a level of connectivity maintained for the local metapopulation.

Passability of barriers - a tool such as the Rapid Passability Assessment Tool developed in Amber Project (https://amber.international/software) can be applied to determine the barrier's impact on fish migration. This, however, requires field data that may not be readily available. Barriers with low impact on the target fish species (index 1) can be considered acceptable. Another tool to assess the passability of barriers is the ICE protocol (Baudoin et al., 2015; Burgun et al. 2015).

5 Concluding remarks

The methodology presented in this guidance makes it possible to identify FFR stretches focusing on longitudinal, lateral and vertical connectivity both within the river stretch and the catchment scale. It contains different steps addressing the different dimensions of connectivity separately.

By definition, a river stretch can only be free-flowing if it fulfils all these criteria. For rivers not fulfilling all criteria, the method will help the user to identify the measures are needed for the river stretch to achieve free-flowing status. This may be through the removal of barriers to continuity within the stretch, or measures addressing off-site pressures elsewhere in the catchment.

Through its modular character, the method can also be used to assess lateral, vertical, and longitudinal connectivity, as well as up-and downstream offsite pressures separately. Even where FFR condition cannot be achieved, there is a merit in reporting partial progress that have increased the free-flowing characteristics at least compared to some of the local assessment criteria.

On an optional basis, Member States can report on progress in restoring river connectivity even in the cases where free-flowing conditions cannot be achieved, so as to showcase their efforts in river restoration. This will be done through field 9.1.1 of the uniform format of NRPs as defined in implementing regulation (EU) 2025/912. This field 9.1.1 is an optional free-text box where MS can explain their “national approach to meeting restoration targets and fulfilling obligations for the natural connectivity of rivers and *natural* functions of the related floodplains, based on latest scientific evidence”. Details on how this partial progress can be reported in this field will be elaborated at as an addendum to the present guidance document in the beginning of 2026.

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List of definitions

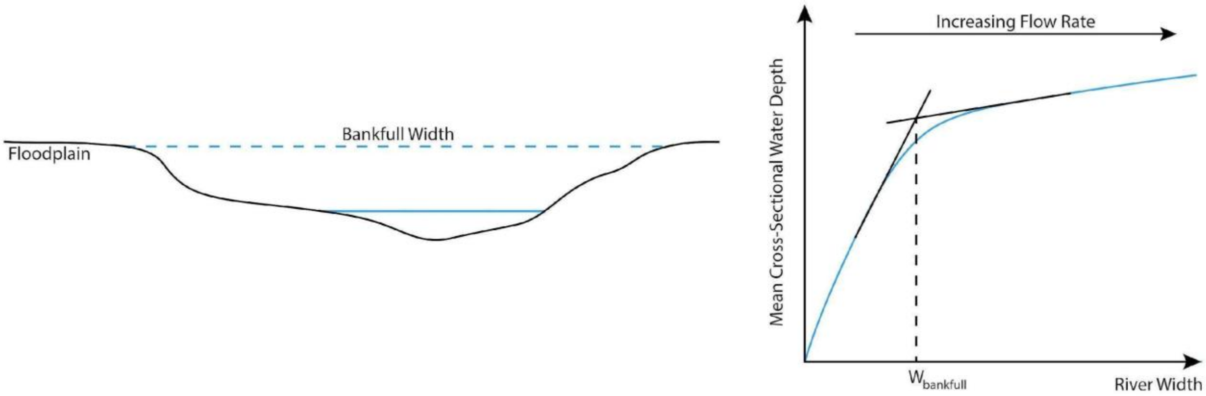
For the purpose of this work, to ensure coherence in all the steps of the proposed criteria, the following definitions are adopted. Some of them may slightly differ from those usually adopted in reference scientific literature (e.g. Rinaldi et al., 2016).

— Anabranching rivers: These are rivers with multiple channels characterized by vegetated islands which divide the flow into several branches in bankfull conditions. Unlike braided rivers, in which in bankfull conditions the bars are completely submerged losing its multi-thread characteristics (except where islands are present), anabranching rivers pattern remains multi-thread even in bankfull conditions. The characterizing parameter is the anabranching index that should be higher than 1.5. The braiding index is variable, but usually close to 1, while the sinuosity index (calculated as the average of the individual channels) can be relatively high, as the individual channels can present a high sinuosity that makes them similar to meandering rivers, even if this parameter is not characterizing. Low-energy lowland anabranching rivers are referred to as anastomosing.

— Attached lateral barrier: Bank protection (e.g. bank walls, gabions, riprap) or artificial levees in direct contact with the riverbanks. Soft/bioengineering techniques (e.g. wooden crib walls, fascines and similar bank protection techniques) are considered equivalent to those of hard engineering for the purpose of this methodology, and they have the same effects on lateral connectivity.

— Bankfull width: It is the lateral extension of the free water surface perpendicular to the river flow direction when the water completely fills the cross-sectional river active channel up to the floodplain or a terrace or hillslope. When the bankfull width is reached, the river bars are entirely submerged, while the river islands (which belong to the floodplain) are not submerged. In cases where multiple channels exist, bankfull width is the sum of the individual channel widths along the cross-section (Washington State Department, 2000). Figure 8 reports a conceptual sketch of bankfull conditions in a single-thread river. In hydrological terms, in the case of a river with a floodplain, the mean cross-sectional water depth grows “rapidly” as the flow rate increases when the flow is entirely confined in the active channel. When the flow starts to invade the surrounding floodplain, the mean cross-sectional water depth grows much less “rapidly”. Ideally, the point at which the slope of the rating curve sharply changes defines the bankfull conditions (and hence the bankfull width, see Figure 8 right panel).

Figure 8- Illustration of bankfull conditions. On the left, the cross-section of a single channel river and its free surface in low flow conditions (continuous light blue line) and bankfull conditions (dashed light blue line). On the right, a quantitative way to define the bankfull width.



— <u>Complex barrier:</u> These types of barriers act on different aspects of the fluvial dynamics, reducing flood magnitude, but also modifying flood routing (Bussettini et al., 2018). This category includes hydraulic structures such as (but not only): channel straightening, flood detention basins, flood deviation channels, cross-section reconfiguration, and flood drainage systems. The effects that these complex barriers induce on river connectivity as well as on hydrological alteration should be assessed on a case-by-case basis as they are difficult to generalize.

— <u>Confined and unconfined river:</u> Following the **degree of confinement** definition (Brierley & Fryirs 2013; Rigon et al., 2013; Rinaldi et al., 2016), a river is confined if more than 90% of the riverbanks are directly in contact with hillslopes or ancient terraces, while a river is unconfined if less than 10% of the riverbank length is in contact with hillslopes or ancient terraces. With values of the degree of confinement in between, the river is partly confined. Equivalently, using the **confinement index** definition, i.e. the ratio between the floodplain width (including the active channel) and the bankfull channel width, the previous classes are now identified as: confined with an index ranging from 1 to 1.5; partly confined with an index ranging from 1.5 to *n*; unconfined with an index higher than *n* (where *n* = 5 for single-thread channels and *n* = 2 for multi-thread or transitional – wandering – morphologies; Rigon et al., 2013; Leopold et al., 2000; Rinaldi et al., 2016).

— <u>Diadromous fish species:</u> Fish that move between fresh and saltwater to complete their lifecycle, spending part of their life cycle in freshwater and another part at sea (Hogan, 2011). They are subdivided in anadromous fish species (spending most of their adult life at sea but spawning in freshwater), and catadromous fish (spending most of their adult lives in freshwater but spawning at sea) and amphidromous fish (regularly migrating from freshwater to seas and vice versa, but not for breeding).

— <u>Ecological flows</u>: A hydrological regime consistent with the achievement of the environmental objectives of the WFD in natural surface water bodies, as mentioned in WFD Article 4(1). (European Commission, 2016).

— <u>Fish mobility:</u> Ability for the movement of an organism, defined as a change in the spatial location of the whole individual in time, driven by processes that act across multiple spatial and temporal scales (Nathan et al., 2008).

— Free-flowing river (FFR): According to the Biodiversity Strategy for 2030 (European Commission, 2022), it is a river that supports connectivity of water, sediment, nutrients, matter and organisms within the river system and with surrounding landscapes, in all of the following four dimensions: i) longitudinal connectivity between up- and downstream; ii) lateral connectivity to floodplain and riparian areas; iii) vertical connectivity to groundwater and atmosphere; and iv) temporal connectivity based on seasonality of fluxes. A FFR is not significantly impaired by anthropogenic barriers in all dimensions of connectivity.

— Hydrological alteration: Artificial alteration of the natural hydrological regime. For the purposes of this document, we consider only those alterations causing a significant barrier for fish migration or sediment transport/composition, e.g. determining a physical disconnection in the surface water flow. Hydropeaking can also fall within this category when causing a barrier for fish migration or sediment transport.

— Homogeneous river reach: A portion of the river stretch with homogeneous characteristics in terms of geomorphological features, where the criteria of this procedure are applied to evaluate longitudinal, lateral and vertical connectivity.

— Hydropeaking: Discontinuous release of turbined water mainly due to peaks of energy demand, causing rapid artificial flow fluctuations into rivers downstream hydropower plants of reservoirs.

— Impoundment: An impoundment is a body of water confined within a man-made enclosure, as a reservoir. It is characterized by a decrease in flow velocity and an increase in residence time.

— Longitudinal connectivity: It concerns the capability of rivers to guarantee (i) the continuity of sediment transport, (ii) the upstream and downstream movement of fish communities, considering both the natural seasonality and the direction of fish migration.

— Lateral connectivity: It concerns the capability of rivers to perform the physical processes of (i) flooding (possibility of overflowing, i.e. presence of a floodplain) and (ii) erosion (hence, lateral mobility).

— Meandering river: Single-channel river (braiding index generally equal to or close to 1), characterized by a sinuous thread with the formation of a more or less regular succession of meanders. A sinuosity index higher than 1.5 classifies a river as meandering. Although this threshold presents a certain arbitrariness, it is commonly accepted in literature (Rinaldi et al., 2016; Leopold et al., 2020) and is adopted in this methodology. The local presence of river islands is possible, but the anabranching index always remains low (lower than 1.5).

— Migratory fish species: Migratory fish are defined according to the Convention on the Conservation of Migratory Species of Wild animals (1979). This includes obligate freshwater fish species (fish that spend their entire life in freshwater) and diadromous (fish that move between fresh and saltwater).

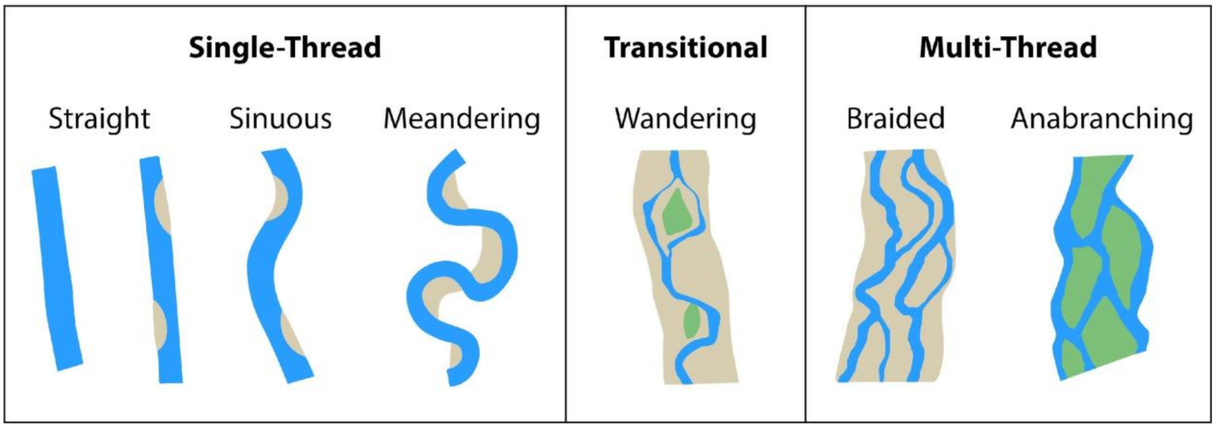
— Natural barriers: Refers to those barriers of natural origin that may be present along a watercourse (such as lakes, waterfalls, beaver dams or landslides) that reduce the connectivity of the watercourse. Given their natural origin, these obstacles are not taken into consideration during the free-flowing assessment.

— Non-attached lateral barrier: This terminology refers to lateral barriers that are not in direct contact with the riverbanks. An example is levees placed in the floodplain or old groynes that are now within the floodplain due to variations in the river path.

- Obsolete barriers: barriers that are no longer needed for renewable energy generation, inland navigation, water supply, flood protection or other uses (NRR recital 50).
- Potamodromous fish species: Migratory fish that spend their whole life cycle in freshwater but migrate over, sometimes, considerable distance (up to 300 km) within catchments.
- River stretch: A river stretch is the piece of river under study where the proposed procedure is applied in order to determine whether the river stretch is free-flowing or not. It can be either very short (a few km) or very long (hundreds of km), depending on the application. In any case, it is composed of at least one or more homogeneous river reaches. In the former case the homogeneous river coincides with the river stretch.
- River type: The basic river typology classification, reported in Figure 8, defines seven river types (straight, sinuous, meandering, wandering, braided, and anabranching, subdivided in three classes, i.e. single-thread, transitional, multi-thread) using readily available information, especially remotely sensed imagery (Rinaldi et al., 2016). In particular, a river is classified based on its planimetric characteristics using the following three indices: i) the **sinuosity index**; ii) the **braiding index**; iii) the **anabranching index**. The sinuosity index is the ratio obtained by dividing the distance measured along the main channel by the distance measured in the direction of the overall planimetric course. The braiding index is determined by counting the number of active channels at baseflow that are separated by bars. Similarly, the anabranching index is determined by counting the number of active channels at baseflow that are separated by vegetated islands. The procedure on how to compute these three indices can be found in many manuals such as the one issued by ISPRA (2016). It is important to note that confined rivers can belong to only four river types, i.e. single-thread, wandering, braided, and anabranching, as, for single-thread rivers, sinuosity is not meaningful as it is imposed by the valley configuration.
- Sinuous rivers: Sinuous rivers have a sinuosity index greater than 1.05 but lower than 1.5. Both in the sinuous rivers and in the straight ones there may be bars, mainly of the lateral type, which often alternate on the two sides. However, the length of the lateral bars is normally less than approximately 80–90% of the stretch. In any case, the braiding and anabranching indices always remain low (e.g. lower than 1.5).
- Straight rivers: Single-channel watercourses, therefore with braiding and anabranching indices generally equal to or close to 1, and with a sinuosity index lower than 1.05 (Rinaldi et al., 2016). Generally, they are indicative of altered situations, as it is a rare morphology in nature and, when present, it is generally not found for stretches longer than ten times the width of the river.
- Vertical connectivity: It concerns the exchange of water, nutrients, matter and organisms between the river and the aquifer via infiltration within the hyporheic zone, which is always present when the riverbed is composed of permeable sediments.
- Wandering rivers: Rivers that have a relatively larger channel width, with rather widespread local braiding situations (therefore a braiding index higher than 1, but lower than 1.5), as well as local anabranching situations, i.e. local presence of islands (therefore also the anabranching index could be higher than 1, but lower than 1.5). The term wandering was introduced precisely to indicate a transition situation between anabranching and meandering, but subsequently the term was extended and used more commonly to transition situations between meandering and multi-thread channels (Rinaldi et al., 2016).

Annex 1. River types considered in the free-flowing rivers procedure

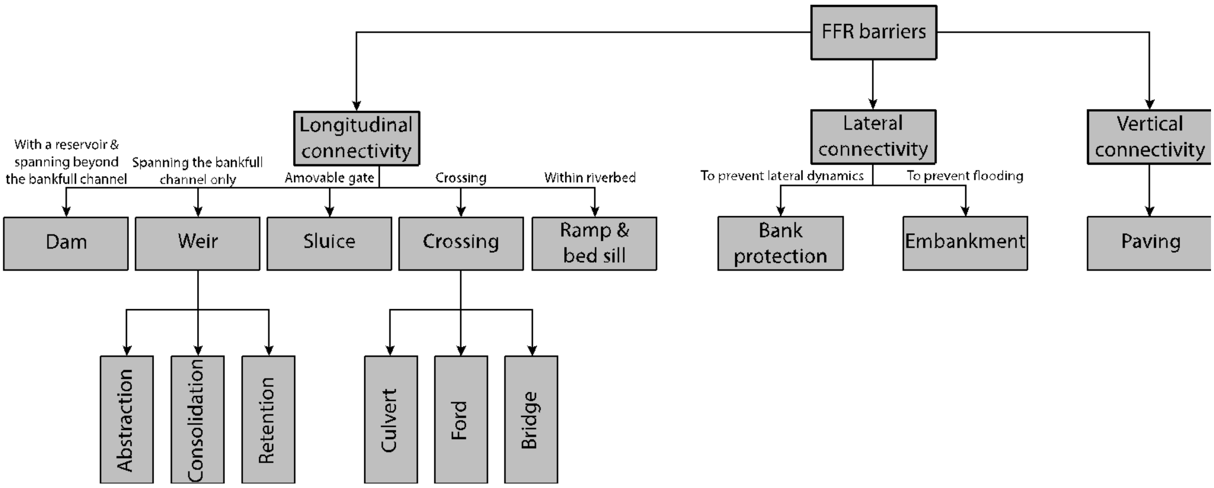
Figure 9: River types considered in the free-flowing rivers procedure



(source: modified from ISPRA, 2016).

Annex 2. Overview of FFR relevant barrier types with their key attributes and impacts

Figure 9: High-level overview of barrier types to be considered in the FFR assessment



A: FFR Barriers - Types

Type	**BANK PROTECTION**
Sub-type	**X**

Definition

Artificial structure aiming at preventing lateral mobility, i.e. bank erosion and/or bank mass movement. Different techniques and materials can be employed, such as bio-engineering techniques based on the use of vegetation and geotextile, or rigid structures such as sacks and blocks or gabions and mattresses. In some cases the bank can be completely covered by artificial material (artificial bank); in other cases, only the bank toe is protected, e.g. with riprap. Types of bank protections include: bank walls, floodwalls, bank stabilisations, and groynes (within the bankfull channel). Bank protection also occurs associated with bridges. Bank protection works are usually attached to the current river banks, but can also be "passive" (at a certain distance from the banks and usually underground, delimiting the mobility corridor where lateral mobility is allowed). Bank protection works can also be located in the floodplain, far from the current banks, when the bankfull has undergone narrowing. Although they do not directly prevent bank erosion they need to be considered, as they reduce lateral mobility. Some protection measures, typically groynes, can also serve to facilitate shipping, navigation and fluvial transport in general (including timber activity and log driving) as well as terrestrial transport (roads, railways, highways, ...). Groynes, in some cases, can have a significant effect both on lateral and longitudinal connectivity for sediments.

Use: protection against erosion and lateral dynamics.

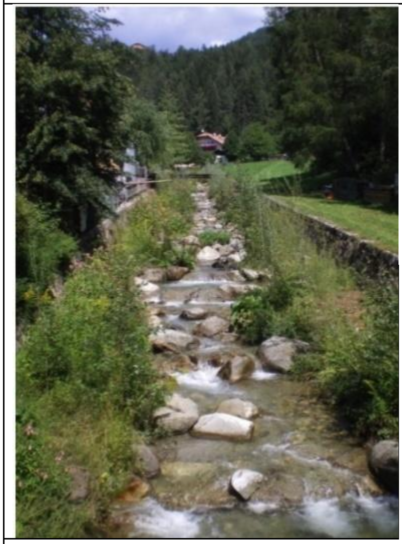
Overview of typical impacts

Bank protection works limit river plan form dynamics, change the riparian substrate, and reduce lateral riparian connectivity and thus the functioning of the riparian zone and oxbows. They may restrict the channel width and ability of biota to migrate. By restricting bank sediment supply, they may also enhance the incision of the riverbed. Higher flow velocities associated with bank protection works lead to bed incisions. Bank protection works may also lead to loss of fish nursery habitat, loss of habitat for macro-invertebrates, and of riparian vegetation.

Impacts on longitudinal/lateral/vertical connectivity

Lateral connectivity mainly
(Groynes protruding within the water channel can also affect longitudinal connectivity)

Pictures



Bank walls

Gabions

Groyne

Bioengineering bank stabilisation

References

Rinaldi et al. 2015, 2016
Picture: Rinaldi et al. 2016

Type	**EMBANKMENT**
Sub-type	**X**

Definition

Embankments (also called dykes or artificial levees) are longitudinal structures, located aboveground, aiming at reducing flooding frequency in the river corridor, therefore conveying a higher discharge within the channel in a range between bankfull discharge and the maximum design discharge.
Embankments can be attached to the bank (thus playing also the role of active bank protection) or at a certain distance within the floodplain, but in any case, all embankments can also be considered an obstacle to lateral mobility. Conversely, not all bank protection types play the role of embankments.
Sometimes these structures can be complex (e.g. two artificial levee systems).
Embankments can also serve to delimitate lateral flood retention basins located outside of the channel.

Use: protection against floods; protection against lateral dynamics.

Overview of typical impacts

Artificial bank protection affects channel morphology and dynamics by restricting the channel width and ability to migrate. Additionally, it limits sediment sources from banks, thereby reducing sediment supply and enhancing erosion of the riverbed. High flows are associated with deeper water depth, contributing to the incision of the bed. Bed incision reduces connectivity between the river and its floodplain. The reduction in lateral connectivity damages the functioning of the riparian zone and also reduces nutrient exchange, and dispersal of biota more widely across the floodplain.

Impacts on longitudinal/lateral/vertical connectivity

Lateral connectivity

Pictures

Earthen levees

Bank-edge levees

Bank walls with the function of levees

Embankment as part of channelisation works for log driving

References

Rinaldi et al. 2015, 2016
Pictures: Rinaldi et al. 2016; https://www.finna.fi/Record/lusto.knp-103664

Type	**DAM**
Sub-type	**X**

Definition

Dams are transversal structures that usually span over the entire riverbed and in many cases beyond the bankfull channel (up to the entire floodplain notably in case of confined channels). Dams block or constrain the flow of water and raise the water level, forming a reservoir or an impounded river segment. Sediments can be completely or partially blocked, depending on the dam structure or dam management.

Dams can be of many forms and types, e.g.: gravity dams, arch dams, buttress dams, movable dams.

Use: water supply, irrigation, and hydropower generation.

Overview of typical impacts

Interruption of sediment transport and longitudinal continuity, an increase of fine substrates, significantly reduced flow velocity upstream (significant impoundment) with the creation of reservoir or impounded river segment and reduced lateral and floodplain dynamic. Risk of hydropeaking (in case of HPP). Water temperature change and other physico-chemical effects. Species composition is altered, e.g. favouring disturbance-tolerant species or still-water species, and change of algae and fish migration is inhibited (physical barrier or absence of current / flow attraction for fish orientation). Impact on groundwater levels. In case modification is linked to drainage schemes, impairment of habitat is also due to the input of fine sediment.

Impacts on longitudinal/lateral/vertical connectivity

Longitudinal connectivity
Vertical connectivity (locally)

Pictures


Dams in mountain (left) and lowland (right) contexts

References

Rinaldi et al. 2015, 2016; OFB 2021
Pictures: AMBER Consortium 2020; Jones et al. 2021

Type	**WEIR**
Sub-type	**General Description**

Definition
Weirs are a broad range of transversal barriers (see sub-types below), generally of smaller size than dams, and where water often flows freely over the top or through the structure. Some types of weirs can cause a ponding effect. Weirs can be accompanied by movable elements (sluice gates). Depending on the type and the location, weirs serve many purposes, including: regulation of flow conditions and water levels, interception of sediment and wood, and reduction of the channel slope for stabilizing the channel bed.
Use: regulation of flow conditions and water levels; water supply and irrigation; intercept sediment and wood; riverbed stabilization.

Type	**WEIR**
Sub-type	**Abstraction Weir**

Definition
Abstraction weirs are used to raise the water level and abstract water for different uses, such as agriculture or hydropower generation (e.g. run-of-the-river structures). Abstraction weirs can also be associated with spillways, i.e. specific diversion channels for flood protection purposes. Weirs can have movable elements. In some cases, temporary transversal structures exist, usually made with local bed sediments to deviate the flow towards an abstraction canal. These are temporary structures (removed by flood or dismantled periodically), but their impact on fish may be relevant.
Use: regulation of flow conditions and water levels; water supply and irrigation.
Overview of typical impacts
Most of the impact depends on size and use and can concern: interruption of sediment transport and longitudinal continuity, increase of fine substrates, reduced flow velocity upstream and reduced lateral and floodplain dynamic (mainly locally) but no significant impoundment. The reduced flow rate in the river stretches between the weir and the hydropower central, and this is especially relevant for small watercourses. Risk of hydropeaking (in case of HPP). Water temperature change and other physico-chemical effects. Local impact on groundwater levels. Species composition is altered, e.g. favouring disturbance-tolerant species or still-water species and change of algae and fish migration is inhibited (physical barrier or absence of current / flow attraction for fish orientation). In case modification is linked to drainage schemes, impairment of habitat is also due to the input of fine sediment; other impacts can occur: on physico-chemistry and water quality; loss of endemic biotas; introduction of alien and often invasive aquatic and terrestrial species; genetic intermixing of separated populations.
Impacts on longitudinal/lateral/vertical connectivity
Longitudinal connectivity; Vertical connectivity (locally)
Pictures
 Abstraction weir with an abandoned mill
References
Rinaldi et al. 2015, 2016; AMBER Consortium 2018; Jones et al. 2021; ANUV 2021 Picture: Jones et al. 2021

Type	**WEIR**
Sub-type	**Consolidation Weir**

Definition

Consolidation weirs aim at stabilizing the channel bed and reducing the channel slope. Depending on their size and type they can also intercept the bedload, at least temporarily. Consolidation weirs can be composite structures (stepped weirs) and occur in series.
These can also be called "bed fall".

Use: reduction of the channel slope for stabilizing the channel bed.

Overview of typical impacts

Interruption of sediment transport and longitudinal continuity, increase of fine substrates, reduced flow velocity upstream and locally reduced lateral and floodplain dynamic. Water temperature change and other physico-chemical effects. Species composition is altered, e.g. favouring disturbance-tolerant species or still-water species, and fish migration is inhibited (physical barrier or absence of current / flow attraction for fish orientation). In case modification is linked to drainage schemes, impairment of habitat is also due to the input of fine sediment.

Impacts on longitudinal/lateral/vertical connectivity

Longitudinal connectivity
Vertical connectivity (locally)

Pictures


Series of consolidation weirs

References

Rinaldi et al. 2015, 2016; LANUV 2021
Picture: Rinaldi et al. 2015

Type	**WEIR**
Sub-type	**Retention Weirs / Check-Dam**

Definition

Retention weirs, also called check-dams, typically located in mountain areas, aimed at intercepting the bedload and large wood fluxes. Their height is usually greater than that of consolidation weirs. The impact on longitudinal connectivity depends on the design/type: they can be a full barrier for fish and most sediments, or be selective and stop only coarse sediments and large wood, without interfering with lower granulometries or with fish passage.

Use: intercept sediment and wood.

Overview of typical impacts

The impact significantly depends on the design. Selective sediment/wood control and bed stabilisation work result in direct habitat loss, including longitudinal connectivity due to changes in substrate, sediment transport, reduced depth, width and flow diversity but to a lesser magnitude than laminar bed stabilisation works. Locally reduced lateral and floodplain dynamic. In mountain contexts flow regime can also be altered.

Impacts on longitudinal/lateral/vertical connectivity

Longitudinal connectivity
Vertical connectivity (locally)

Pictures

Selective retention weir

References

Rinaldi et al. 2015, 2016; Betta et al. 2008
Picture: Betta et al. 2008

Type	**SLUICE (lock)**
Sub-type	**X**

Definition

Sluice is a barrier with one or more movable gates aimed at allowing ships/boats to navigate obstructions that create uneven levels of water along river and canal waterways. Furthermore, sluices can be small structures that serve to regulate water levels and help water diversions or water abstractions. They also serve to close waterways to prevent areas from flooding (e.g. sluices built in embankments). On lowlands and in small rivers sluices are the main water regulation works.

Use: regulation of water levels, ship locks, navigation.

Overview of typical impacts

The impact depends on size and use as well as on BRT. In the case of MT river types, it often impacts river morphology (artificial cut-off, reduction of active channel width, loss of lateral connectivity within floodplain).

Impacts on longitudinal/lateral/vertical connectivity

Longitudinal connectivity

Pictures

Ljubljanica sluice gate

References

Rinaldi et al. 2015, 2016; AMBER Consortium 2018; Jones et al. 2021; LANUV 2021
Picture: Wikipedia (https://en.wikipedia.org/wiki/Ljubljanica_Sluice_Gate)

Type	**CROSSING STRUCTURES**
Sub-type	**General Description**

Definition

Crossing structures include a broad range of transversal barrier types (see sub-types below), the main purpose is to help people to cross or wade the river. Depending on the type and size, the crossing structure can span entirely or partially the riverbed.

Use: river crossing.

Type	**CROSSING STRUCTURES**
Sub-type	**Culvert**

Definition

A culvert is a structure aimed at carrying a stream or river under an obstruction (often secondary roads, forest track or rail). It varies in form from round and elliptical to box-shaped.

Use: carrying a stream or river under an obstruction.

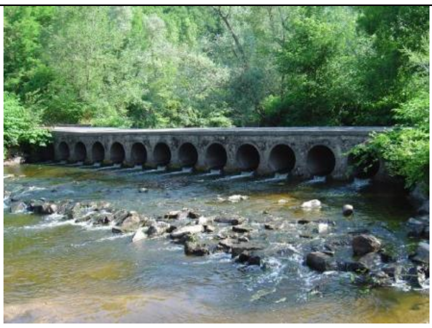
Overview of typical impacts

River covering results in severe loss and other impacts on habitats (including longitudinal, alongshore, transversal, and vertical connectivity) both directly and due to radical changes in substrate, sediment transport, flow regime, and lack of structural elements. Only local Impact on groundwater.

Impacts on longitudinal/lateral/vertical connectivity

Longitudinal connectivity mainly

Pictures



Round (left) and box-shaped (right) culverts

References

Rinaldi et al. 2015, 2016; AMBER Consortium 2018; Jones et al. 2021; OFB 2021
Picture: OFB 2021; https://www.theengineeringcommunity.org/different-uses-of-box-culverts/

Type	**CROSSING STRUCTURES**
Sub-type	**Ford**

Definition

A ford is a low-head channel structure which creates a shallow section for crossing or wading the river or stream that can be submerged at high flow conditions. Fords create a fixed portion of the riverbed, usually not causing significant alterations in sediment dynamics. Depending on the design, the impact on longitudinal connectivity for fish can be more or less relevant.

Use: river crossing.

Overview of typical impacts

Only local impact on river morphology, bed substrated and habitats. Depending on the species, the impact can be more or less significant.

Impacts on longitudinal/lateral/vertical connectivity

Longitudinal connectivity mainly
(Depending on the design and material, fords can locally nullify the vertical connectivity)

Pictures

Fords. On the right, a ford with culverts

References

Rinaldi et al. 2015, 2016; AMBER Consortium 2018; Jones et al. 2021; Januchowski-Hartley et al. 2013
Pictures: OFB 2021; AMBER 2018

Type	**CROSSING STRUCTURES**
Sub-type	**Bridge**

Definition

Bridges are crossing structures with a wide range of forms and sizes, which represent partial barriers to longitudinal connectivity. The barrier effect on fish and sediment connectivity is generally negligible and linked to associated stabilisation sills (REFER TO SILLS IN THE ANALYSIS). The barrier effect might be significant on connectivity for large wood and is strongest for bridges with riverbed piles, single spans and low heights (e.g. equal or lower than bankfull water level).
Bridges with riverbed piles are often associated with bed sills.

Use: river crossing.

Overview of typical impacts

The impact depends on the level of interference of the piles, the number of arches and size (arch height and width) as well as on density of structures. Only local Impact on groundwater (related to piles basement).

Impacts on longitudinal/lateral/vertical connectivity

Longitudinal connectivity mainly

Pictures

Bridge with a single arch of a low size

High single arch bridge but with a small width, not enough to allow intense transport of large woods

References

Rinaldi et al. 2016; OFB 2021
Pictures: Betta et al. 2008; Rinaldi et al. 2016

Type	**RAMP**
Sub-type	**X**

Definition

Ramps are local riverbed stabilisation structures, located within the channel, made with rocks of different sizes. These are generally low-head structures not protruding significantly outside of the riverbed, but extending longitudinally. The impact on sediment connectivity is usually limited and linked to the local slope reduction. The impact on fish depends on the design and species. Ramps can be built downstream to sills or weirs as a mitigation measure to improve connectivity for fish.

Use: control channel dynamics (reducing channel slope and riverbed erosion).

Overview of typical impacts

Local interception of sediment and reduction of river dynamics (vertical and longitudinal); habitat loss and effect on local river morphology (reduced slope, flow velocity, channel width, changes in geomorphic units). Only local Impact on groundwater.

Impacts on longitudinal/lateral/vertical connectivity

Longitudinal connectivity
Vertical connectivity (locally)

Pictures

Ramp with boulders

References

Rinaldi et al. 2015, 2016; AMBER Consortium 2018; Jones et al. 2021
Picture: Jones et al. 2021

Type	**BED SILL**
Sub-type	**X**

Definition

Bed sills are transversal structures located within the channel, aimed at locally stabilizing the channel bed. These are typically low-head structures not protruding significantly outside of the riverbed. The impact on sediment connectivity is usually limited and linked to the local slope reduction. The impact on fish can be more or less relevant depending on the height and species. Sills are often associated with bridges and bridge piles.
These can also be called "ground sill".

Use: bridge protection (river crossing), controlling channel dynamics locally (reducing channel slope and riverbed erosion).

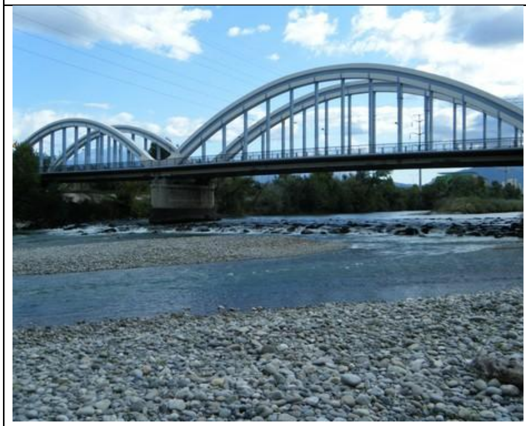
Overview of typical impacts

River bed stabilisation works result in modified substrate, change in morphology, depth, and width, reduced fine sediment input, loss of river bed invertebrate and plant species and loss of shelter for fish and invertebrates.

Impacts on longitudinal/lateral/vertical connectivity

Longitudinal connectivity
Vertical connectivity (locally)

Pictures



Bed sill associated with a bridge (Obstacle ROE37561).

Bed sill in lowland river

References

Rinaldi et al. 2015, 2016; AMBER Consortium 2018; Jones et al. 2021; OFB 2021; Betta et al. 2008; LANUV 2021
Picture: OFB (application GEOBS); LANUV 2021

Type	**PAVING**
Sub-type	**X**

Definition

The paving of the riverbed, often coupled with bank protections, aims to diminish the resistance to the flow. This leads to a decrease in water levels and an acceleration of the current's velocity. Alternatively, it serves to protect other hydraulic structures from localized erosion, which could undermine their foundations. Examples include bridge piers and the downstream sections of weirs or dams.

Use: immobilize a river stretch; reduce the resistance to the flow; increase river channel conveyance capacity.

Overview of typical impacts

The impacts can primarily be attributed to a significant decrease, if not complete cessation, of hyporheic and groundwater exchanges. The riverbed configuration is drastically altered. Consequently, local ecosystems suffer destruction. Furthermore, solid transport and localized erosion are hindered along the entire length of the paved section.

Impacts on longitudinal/lateral/vertical connectivity

Vertical connectivity, longitudinal connectivity

Pictures

Los Angeles River (concrete paving)

References

Rinaldi et al. 2016
Picture: https://lariver.org/blog/about-la-river

B: FFR Barriers – Attributes

		Why do we need the attribute							
Attribute	**Description**	**Reporting (WFD)**	**Connec-tivity Assess-ment**	**Moni-toring**	**Miti-gation**	**Comments**	**Applicability (Longitudi-nal, Lateral and Vertical Connecti-vity)**	**Priority Attribute**	**Key References**
Water body information	Country, basin, river	X		X		Knowing the river, basin, and country where the barrier is located provides basic information to be used for many purposes notably reporting (link with WFD) and monitoring.	Longitudinal: OK Lateral: OK Vertical: OK	In case of barriers to lateral connectivity	
Location	Geographic coordinates (X, Y) or other geographic information		X	X		The exact location of barriers is important for impact assessment (estimate fragmentation, effects on biota…) as well as for monitoring purposes. X and Y coordinates have to be mandatory for barriers to longitudinal connectivity. Ideally, information on the base map or river network used to define X and Y coordinated should also be provided. For lateral and vertical connectivity, it is difficult to assign accurate X and Y coordinates for structures like dykes or extensive bank protections. In that case, it would be useful to include GIS support.	Longitudinal: OK Lateral: NA (see "Comments") Vertical: NA (see "Comments")	In case of barriers to longitudinal connectivity	AMBER (D1.2; Belletti et al. 2020; Jones et al. 2021)
BRT	Basic River Typology, including information on altitude and river size		X	X		This information is relevant as different river types show different sensitivity and hence different responses to different pressures (impact assessment) or mitigation measures.	Longitudinal: OK Lateral: OK Vertical: OK	Yes	Rinaldi et al., 2016a, b; Gurnell et al. 2014 (& WFD CIS-WG2014)
Existing inventory	Source ID, URL, reference	X		X		This information is important for many purposes, above all for updating and monitoring the framework of WFD reporting and for EU scale assessments of FFR status.	Longitudinal: OK Lateral: OK Vertical: OK	Highly recommended	AMBER (D1.2; Belletti et al. 2020; Jones et al. 2021)
FFR barrier type	Barrier type based on FFR types		X		X	Barrier type can be used as a proxy for impact assessment because the type is linked to specific sizes and uses and as a consequence affects connectivity. The FFR barrier typology includes broad categories of barrier types. If member states use more detailed barrier types, they can indicate a specific barrier type (type 2 or source type) in addition to the FFR barrier type.	Longitudinal: OK Lateral: OK Vertical: OK	Yes	AMBER (D1.2; Belletti et al. 2020; Jones et al. 2021); OFB 2021; Rinaldi et al. 2016b; Sandre 2014; FFR core group

Year	Date of construction (end)				X	Age could be used as a proxy for barrier status (mitigation purposes), but could also be useful for long-term impact assessment. Barriers in Europe vary widely in age and many are over 50 years old, possibly not in use anymore or close to being decommissioned. This information is difficult to obtain.	Longitudinal: OK Lateral: OK Vertical: OK	No (difficult to obtain)	AMBER (D1.2; Belletti et al. 2020; Jones et al. 2021)
Height	Barrier height (m) or height classes		X		X	Barrier height can be used as a proxy for impact assessment (e.g. to estimate passability for different biota or impoundment sizes). Barriers of different sizes have different effects on connectivity but potentially any size can significantly impact on at least one river component (water, sediment, wood, nutrient/matter, organisms). It is also useful to characterise in detail the FFR barrier type size for mitigation purposes (prioritization). The recommended definition is: "vertical distance between the lowest point on the crest of the barrier and the lowest point in the original streambed". In case this definition doesn't correspond to the one used for the national inventories/methodologies, use other ways to estimate it (e.g. height classes). In the case of bridges, height means arch height (clear height), measured at the highest point from the water surface to the bottom edge of the structure.	Longitudinal: OK Lateral: OK Vertical: NO	Yes	AMBER (D1.2; Belletti et al. 2020; Jones et al. 2021); LANUV 2021
Width	Barrier extent across the river channel (full extent, partial extent), the banks or the floodplain		X			Barrier width can be used as a proxy for impact assessment (e.g. to estimate the impact extent of barrier pressures on connectivity). For e.g., a full-extent weir is likely to have a higher impact on longitudinal connectivity compared to one that spans only a portion of the river width. Barrier width is also useful to characterise in detail FFR barrier types. For e.g. in terms of size: the width extent of a bank protection allows us to appreciate the efficiency of the structure against lateral dynamics; in terms of impact: weirs with movable gates	Longitudinal: OK Lateral: OK Vertical: OK	Yes	AMBER (D1.2; Belletti et al. 2020; Jones et al. 2021); LANUV 2021

						impact on connectivity only temporarily. Lateral retention basins can be included in the measure of width extent. In the case of bridges, height means arch width (clear width), measured at the broadest position inside of the construction.			
Distance	The distance to the active channel: from 0 (bank covering, groynes) to floodplain extent		X			The distance of embankment structures is relevant for impact assessment of lateral connectivity (notably lateral dynamics), where the structures closest to the active channel are those with higher impact on lateral connectivity. Some embankments or bank protection structures in European rivers are old but relevant for mid- long-term channel dynamics assessment.	Longitudinal: NO Lateral: OK Vertical: NO	Yes	Rinaldi et al. 2016b
Extent (longitudinal)	Barrier longitudinal extent along the river		X			The longitudinal extent along river channels or riverbanks is a proxy for the impact assessment of barriers to lateral and vertical connectivity. Dense or extended bank protections or embankments have a higher impact on lateral connectivity compared to isolated structures. Barrier longitudinal extent is also useful to characterise in detail FFR barrier types in terms of size.	Longitudinal: NO Lateral: OK Vertical: OK	In case of barriers to lateral and vertical connectivi ty	Belletti et al. 2015; Rinaldi et al. 2016b
Operation / use(s)	The purpose the barrier serves (one or more): water supply, hydropower generation, flood protection, flow regulation (water, sediment, wood), bank protection, river control (bed stabilization, dynamics, fluvial transport), aquatic activities (aquaculture, recreation)	X	X		X	Barrier operation or use is useful to better characterise the FFR barrier typology (refine the type). It is required to identify HMWB (WFD reporting). This information also serves for impact assessment (e.g. in case of multiple uses), and for mitigation purposes (prioritization based on use).	Longitudinal: OK Lateral: OK Vertical: OK	Yes	OFB 2021; Sandre 2014
The presence of movable gates	Elements to ensure transparency for sediments in flood conditions		X				Longitudinal: OK Lateral: OK Vertical: NO	No	
In-use status	The barrier serves or not		X	X	X	The information on barrier status is useful for	Longitudinal: OK	Yes	Sandre 2008; AMBER

	the purpose for which it has been built: in project, in construction, operational, damaged, removed					mitigation purposes. For e.g., many barriers are no longer in use and can prioritized for removal. This can also be used for impact assessment (e.g. the impact of an abstraction weir to service an abandoned water mill is lower than one still in use). Information on barrier status should be recorded for monitoring purposes.	Lateral: OK Vertical: OK		(D1.2; Belletti et al. 2020; Jones et al. 2021)
Mitigation measure(s)	Indicate the presence and type of mitigation measure: fish pass; sediment pass/valves; berms (passable strip of land (natural or artificial) to allow animals to cross the barrier; by-pass channel		X		X	The presence of mitigation measures is important to support a better assessment of barrier impact. It is also useful to support the prioritization of further mitigation measures. This information is scattered on existing inventories.	Longitudinal: OK Lateral: OK Vertical: OK	Yes	AMBER (D1.2; Belletti et al. 2020; Jones et al. 2021); LANUV 2021
Complex structure	Indicate if the barrier is part of a more complex structure (e.g. weir with movable elements/sluice)			X	X	The information on the existence of other structures associated with the barrier is useful for barrier monitoring and mitigation. This is quite common in large European rivers (e.g. see barriers along the Rhone River). The fact a barrier is part of a complex structure can be used to characterize more in detail FFR barrier types and impact. A description of the complex structure is optional.	Longitudinal: OK Lateral: OK Vertical: OK	No	Sandre 2008

C: Impact Description

HYMO IMPACTS	DESCRIPTION
Hydrology: quantity and dynamics of flow	This is associated with longitudinal, lateral and vertical artificial barriers, but not all barriers have the same effect. As well, the impact can be on quantity or on dynamics (not necessarily on both contemporarily). It also includes effects on flood and drought risk.
Hydrology: impoundment	Significant reduction of the flow velocity inconsistent with the BRT. This has cascading effects on morphology (meso- and microscale habitats), vertical connectivity, riparian structure, floodplain structure, thermal regime and other physico-chemical parameters, and BQEs and overall ecology.
Hydrology: hydropeaking	Associated to barriers specifically used for hydropower production. It can have multiple effects, mainly when (artificial/non-mitigated) rapid flow alterations are released downstream HP tailrace into rivers, like continuity, morphology, physico-chemistry and survival (flushing/stranding) of BQEs and overall ecology. For ex., hydropeaking reaches may be physical barriers to fish migration.
Hydrology: connection to groundwaters	It concerns vertical connectivity and some FFR barrier types can have a local effect on groundwater connection and hyporheic exchanges.
River longitudinal continuity: flow	Not all barriers have the same effects on the 3 different components, these deserve to be identified separately. Both bedload and suspended sediment have to be taken into account. Effects of a barrier on continuity for sediment and wood can propagate downstream and upstream.
River longitudinal continuity: sediment	
River longitudinal continuity: wood	
River continuity: lateral dynamics	This includes both bank erosion processes and channel dynamics (lateral migration).
Morphology: river width and depth	Reach and geomorphic unit scale (mesoscale habitats): bed incision; channel narrowing; changes in geomorphic unit types and channel planform; homogenization; changes in geomorphic unit size. The effects can propagate at the segment scale (downstream and upstream).
Morphology: riverbed structure, substrate	Local-scale topography and sediment characteristics (microscale habitats): riverbed homogenization, armouring, clogging; effects on vertical connectivity; effect on the thermal regime.
Morphology: riparian zone structure	This is associated with the presence of structures (e.g. dam impacts) as well as to the changes in lateral dynamics. This has effects on banks and riparian habitats availability and heterogeneity, as well as on physico-chemistry (food and nutrients).
Morphology: floodplain structure	Floodplain habitat and connectivity between the river and its floodplain (beyond riparian zone; secondary arms, oxbow lakes, wetlands…).

D: References used in Annex 2

REFERENCE	TYPE & NOTES	URL
AMBER Consortium, 2016. D.1.1 Guidance on Stream Barrier Surveying and Reporting	AMBER deliverables and publications	https://amber.international/wp-content/uploads/2020/12/D1.1-Guidance-on-Stream-Barrier-Surveying-and-Reporting.pdf
AMBER Consortium, 2018. D1.2 Country-specific reports containing the metadata	AMBER deliverables and publications	https://amber.international/wp-content/uploads/2020/12/D1.2-Country-specific-Reports-Containing-the-Metadata.pdf
AMBER Consortium, 2020. Let it Flow. Best Guidance on Barrier Management in Rivers. https://amber.international/magazine/	AMBER deliverables and publications (AMBER digital magazine)	https://amber.international/wp-content/uploads/2020/10/AMBER-magazine-Digital.pdf
APAT, 2003. Atlante delle opere di sistemazione fluviale	Atlas of river engineering works, Italy	https://www.isprambiente.gov.it/contentfiles/00003400/3494-atlante-delle-opere-di-sistemazione-fluviale.pdf/
Belletti, B., Garcia de Leaniz, C., Jones, J., Bizzi, S., Börger, L., ..., Zalewski, M., 2020. More than one million barriers fragment Europe's rivers. *Nature* 588, 436–441. https://doi.org/10.1038/s41586-020-3005-2	AMBER deliverables and publications Relevant info for longitudinal barriers (barrier types, connectivity measures and impacts)	https://amber.international/peer-reviewed-publications/
Belletti, B., Rinaldi, M., Buijse, A.D., Gurnell, A.M., Mosselman, E., 2015. A review of assessment methods for river hydromorphology. *Environmental Earth Sciences* 73, 2079–2100. https://doi.org/10.1007/s12665-014-3558-1	REFORM deliverables and publications. A review of hymo assessment methods related to WFD	https://link.springer.com/article/10.1007/s12665-014-3558-1
Betta G., Iorio L., Porro E., Silvestro C., 2008. Manuale per il censimento delle opere in alveo. Provincia di Torino. Regione Piemonte. ISBN: 88-901200-3-7	Guidebook for the census of in-channel structures of the Piemonte region, Italy	http://gis.csi.it/disuw/sicod/doc/manuale_censimento_opere.pdf
EC WFD CIS Guidance No 37 - Mitigation Measures Library.xlsx	Mitigation measure library in the framework of the assessment/definition of ecological potential for HMWBs. The xls file contains information on the impact of artificial structures on different river components (hymo & BQE)	https://circabc.europa.eu/ui/group/9ab5926d-bed4-4322-9aa7-9964bbe8312d/library/67f969f9-5abe-4765-a952-2f8e2bf5b664/details
EC, 2021. Biodiversity Strategy 2030. Barrier Removal for River Restoration	Guidance for barrier removal prepared in the framework of the BDS2030 for obtaining 25k km of free-flowing rivers	https://environment.ec.europa.eu/system/files/2021-12/Barrier%20removal%20for%20river%20restoration.pdf

Gurnell et al. 2014. A hierarchical multi-scale framework and indicators of hydromorphological processes and forms.	REFORM deliverables and publications (D2.1 - Hymo framework). It contains information on the rationale for the river typology	https://www.reformrivers.eu/system/files/D2.1%20Part%201%20Main%20Report%20FINAL.pdf
Januchowski-Hartley, S.R., McIntyre, P.B., Diebel, M., Doran, P.J., Infante, D.M., Joseph, C., Allan, J.D., 2013. Restoring aquatic ecosystem connectivity requires expanding inventories of both dams and road crossings. *Frontiers in Ecology and the Environment* 11, 211–217. https://doi.org/10.1890/120168	Article on the extent and effect of road crossing on aquatic ecosystems (UK)	https://esajournals.onlinelibrary.wiley.com/doi/abs/10.1890/120168
Jones J., Garcia de Leaniz C., Belletti B., Borger L., Bizzi S., Segura G., Van-de-bund W. (2021). Quantifying river fragmentation from local to continental scales: data management and modelling toolbox. Authorea. DOI: 10.22541/au.159612917.72148332	AMBER deliverables and publications. Relevant info for longitudinal barriers (barrier types, connectivity measures and impacts)	https://amber.international/peer-reviewed-publications/
Keruzoré, A.A., Willby, N.J., Gilvear, D.J., 2013. The role of lateral connectivity in the maintenance of macrophyte diversity and production in large rivers. Aquatic Conservation: *Marine and Freshwater Ecosystems* 23, 301–315. https://doi.org/10.1002/aqc.2288	Scientific publication on the role of lateral connectivity in the maintenance of macrophyte diversity and production in large rivers.	https://onlinelibrary.wiley.com/doi/full/10.1002/aqc.2288
Knox, R.L., Wohl, E.E., Morrison, R.R., 2022. Levees don't protect, they disconnect: A critical review of how artificial levees impact floodplain functions. *Science of The Total Environment* 837, 155773. https://doi.org/10.1016/j.scitotenv.2022.155773	Review article on the negative effects of artificial levees	https://www.sciencedirect.com/science/article/abs/pii/S0048969722028704
LANUV, 2021. River constructions in North Rhine-Westphalia Guide for the field survey of constructions in rivers	Field guidebook for river barriers in North Rhine-Westphalia	https://www.lanuv.nrw.de/fileadmin/lanuv/veroeffentlichungen/arbeitsblatt/arbla38_EN/LANUV-Arbeitsblatt_38_River_constructions.pdf
OFB, 2021. Manuel d'utilisation de l'application Module ROE. Référentiel des Obstacles à l'Ecoulement	Guidebook for the application of the ROE application (OFB, French Institute for Biodiversity)	NA
OFB, application GEOBS. Référentiel des Obstacles à l'Ecoulement et Informations sur la Continuité Ecologique Version: 5.5.19	Web application OFB - GEOBS. For the survey of barriers to river continuity	NA
Burgun V., Chanseau M., Kreutzenberger K. (Coord.), Marty V., Pénil C., Tual M., Voegtlé B. (2015). ICE.	Protocol to assess river continuity in France and	https://patbiodiv.ofb.fr/fiche-methodologique/continuite-ecologique/description-champs-

Informations sur la continuité écologique. Protocole de terrain pour l'acquisition des données. Onema. Collection Guides et Protocoles, 84p.	online application (ROE-ICE)	dapplication-methode-linformation-continuite-ecologique-ice-362
REFORM WIKI. Category: Pressures	The wiki of the REFORM project with information on hydromorphological and ecological pressures of anthropogenic activities	https://wiki.reformrivers.eu/index.php?title=Category:Pressures
Rinaldi, M, Bussettini, M., Surian, N., Comiti, F., Gurnell, A.M., 2016. Guidebook for the evaluation of stream morphological conditions by the Morphological Quality Index (MQI).	REFORM deliverables and publications (D6.2 - Guidebook MQI). Relevant information on the impact of barriers on hymo and ecology.	https://www.reformrivers.eu/guidebook-evaluation-stream-morphological-conditions-morphological-quality-index-mqi
Rinaldi, M., Belletti, B., Comiti, F., Nardi, L., Bussettini, M., Mao, L., Gurnell, A.M., 2015. The Geomorphic Units survey and classification System (GUS).	REFORM deliverables and publications (D6.2 - Guidebook GUS)	https://www.reformrivers.eu/geomorphic-units-survey-and-classification-system-gus
Rinaldi, M., Gurnell, A.M., del Tánago, M.G., Bussettini, M., Hendriks, D., 2016a. Classification of river morphology and hydrology to support management and restoration. *Aquatic Sciences* 78, 17–33. https://doi.org/10.1007/s00027-015-0438-z	REFORM deliverables and publications (EU Basic River Typology (BRT))	https://doi.org/10.1007/s00027-015-0438-z
Rinaldi, M., Surian, N., Comiti, F., Bussettini, M., 2016b. IDRAIM - Sistema di valutazione idromorfologica, analisi e monitoraggio dei corsi d'acqua (Versione aggiornata 2016 No. 132/2016), Manuali e Linee Guida. ISPRA, Roma.	IDRAIM guidebook Hymo methodology used in Italy	www.isprambiente.gov.it/it/pubblicazioni/manuali-e-linee-guida/idraim-sistema-di-valutazione-idromorfologica-analisi-e-monitoraggio-dei-corsi-d2019acqua-versione-aggiornata-2016
Sandre, 2008. Obstacles à l'écoulement. Thème: Ouvrages. Version 1.0	Base documents of the ROE French system	http://sandre.eaufrance.fr/ftp/documents/fr/ddd/obs/1.0/sandre_presentation_OBS_1.0.pdf
Sandre, 2014. Description des ouvrages faisant obstacle à faisant obstacle à l'écoulement l'écoulement. Ouvrages. Version 1.2	Description of river obstacle structures	https://www.sandre.eaufrance.fr/notice-doc/description-des-ouvrages-faisant-obstacle-%C3%A0-l%E2%80%99%C3%A9coulement
Sandre, 2012. Obstacles à l'écoulement. Présentation. Thème : Ouvrages. Version 1.1.	Online Atlas of barrier types in France	https://www.sandre.eaufrance.fr/atlas/srv/fre/catalog.search#/metadata/59057026-b40c-4cf9-9e3e-7296e0aa1a78
Stoffels, R.J., Humphries, P., Bond, N.R., Price, A.E., 2022. Fragmentation of lateral connectivity and fish population dynamics in large rivers. *Fish and Fisheries* 23, 680–696. https://doi.org/10.1111/faf.12641	Scientific paper on the effects of lateral hydro connectivity on fish; lateral connectivity also has an effect on the longitudinal dimension at the basin scale.	https://onlinelibrary.wiley.com/doi/full/10.1111/faf.12641

Surian, N., Rinaldi, M., 2003. Morphological response to river engineering and management in alluvial channels in Italy. *Geomorphology* 50, 307–326. https://doi.org/10.1016/S0169-555X(02)00219-2	Scientific article on impacts of engineering measures on river morphology.	http://www.sciencedirect.com/science/article/pii/S0169555X02002192

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KH-01-25-233-EN-N

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