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Criteria for identifying free-flowing river stretches for the EU Biodiversity Strategy for 2030

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Contents

Abstract

The EU Biodiversity Strategy includes the target that at least 25000 km of rivers should be restored into free-flowing rivers by 2030 through the removal of primarily obsolete barriers and the restoration of floodplains and wetlands. This document proposes criteria for identifying free-flowing rivers, taking into account longitudinal, lateral, and vertical connectivity at local and catchment scales. The aim is to provide a tool that can be used by authorities to determine the length of free-flowing rivers in their catchments. In addition, the tool can be used to predict the increase in free-flowing river length resulting from barrier removal and other restoration measures. This will help prioritising measures that can contribute to the 25,000 km target.

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

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1 Introduction

The importance of river restoration and free-flowing rivers (FFR) is increasingly recognized by European environmental policy. While the notion of free-flowing rivers is not yet defined in EU environmental legislation, the Commission's interpretation is that free-flowing rivers are rivers that are not impaired by artificial barriers and are not disconnected from their floodplain, thus allowing the free movement of water, sediment, fish and other organisms. The Water Framework Directive (WFD) and the Biodiversity Strategy 2030 are of particular importance in this context.

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. Moreover, such fragmentation may lead to significant adverse effects on the stability of infrastructures and riverine settlements. The WFD sets the objective of good ecological status, or good ecological potential, for all waters in the EU by 2015, with the possibility of extending the deadline until 2027 under certain conditions. River continuity is one of the hydromorphological quality elements that contribute to good ecological status.

However, river continuity in WFD focuses primarily on the longitudinal dimension of connectivity. For this reason, besides calling for better implementation of existing legislation on freshwater, the Biodiversity Strategy 2030 reinforced the importance of restoring the natural connectivity of rivers by setting a target that broadens the focus of restoration to lateral connectivity and to the need to reconnect rivers to their floodplain: "*at least 25000 km of rivers to be restored into free-flowing rivers by 2030 through the removal of primarily obsolete barriers and the restoration of floodplains and wetlands*".

The Biodiversity Strategy 2030 also sets an obligation for the European Commission to provide technical guidance to help Member States identify sites for river restoration and help mobilise funding. DG Environment in the European Commission, together with the Joint Research Centre, led the initiative to prepare such guidance by the end of 2021 and published a document titled "Biodiversity Strategy 2030: barrier removal for river restoration" (EC, 2022).

According to this guidance document, the 25000 km FFR target aims to achieve stretches of free-flowing rivers within a network of continuous rivers, i.e. complying with the WFD's rules (WFD – barriers are either taken down or adapted to allow the achievement of good ecological status). The guidance document also recognises the need for the definition of free-flowing rivers to be made operational and fit for the European context, to promote river restoration actions. To do so, the guidance document proposes to define, in a joint effort of the Commission and the Member States, a set of criteria to be able to assess whether a (stretch of a) river is free-flowing or not.

For this purpose, and to help with the practical implementation of the Biodiversity Strategy's targets on river restoration, the Free-flowing Rivers (FFR) Core Group has been established under the ECOSTAT working group, with a mandate to develop such criteria.

This document reports the criteria for identifying free-flowing rivers, set out in a methodology that has been developed by the FFR Core Group. This document was discussed with the ECOSTAT group and other stakeholders. The aim is to provide a tool that can be used by authorities to determine the length of free-flowing rivers in their catchments. In addition, the tool can be used to predict the increase in free-flowing river length resulting from barrier removal and other restoration measures. This will help prioritising measures that can contribute to the 25,000 km target.

2 Basic principles

The following methodology is a procedure that Member States (MS) can apply to selected river stretches to assess whether they can be considered free-flowing, under current conditions or after the implementation of restoration measures. Furthermore, it can be applied more extensively, e.g. to assess the current status of river connectivity at the river basin or national level.

Given the four dimensions of connectivity within riverine systems, the presented methodology focuses on the three dimensions most directly affected by physical barriers, i.e. longitudinal, lateral, and vertical connectivity, while temporal connectivity is partly taken into account, in particular by considering ecological flows. Temporary rivers can be included in the assessment if their unimpacted connectivity is properly taken into account as reference, in order to distinguish between natural and human-induced lack of 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.

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 report. 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 Biodiversity Strategy 2030 and of this methodology. The methodology consists of four assessment steps, which do not necessarily need to be applied in the order of this report.

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 that 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 methodology to different technical needs, e.g. choosing from a national to local scale, combining the screening tool 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 as reported in the H2020 AMBER project[1]). This methodology can help establish whether some of these stretches can achieve FFR status.

The procedure comprises the following four steps, which are logically linked to each other but do not necessarily have to be carried out sequentially (Figure 1):

- Step 1 – Identification of homogenous river reaches within the potential FFR stretches
- Step 2 – Homogeneous reach assessment
    - Addressing longitudinal connectivity
    - Addressing lateral connectivity
    - Addressing vertical connectivity
- Step 3 – Large-scale assessment of upstream and downstream pressures on potential FFR stretch
- Step 4 – Minimum length of potential FFR stretch

Step 2 addresses 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.

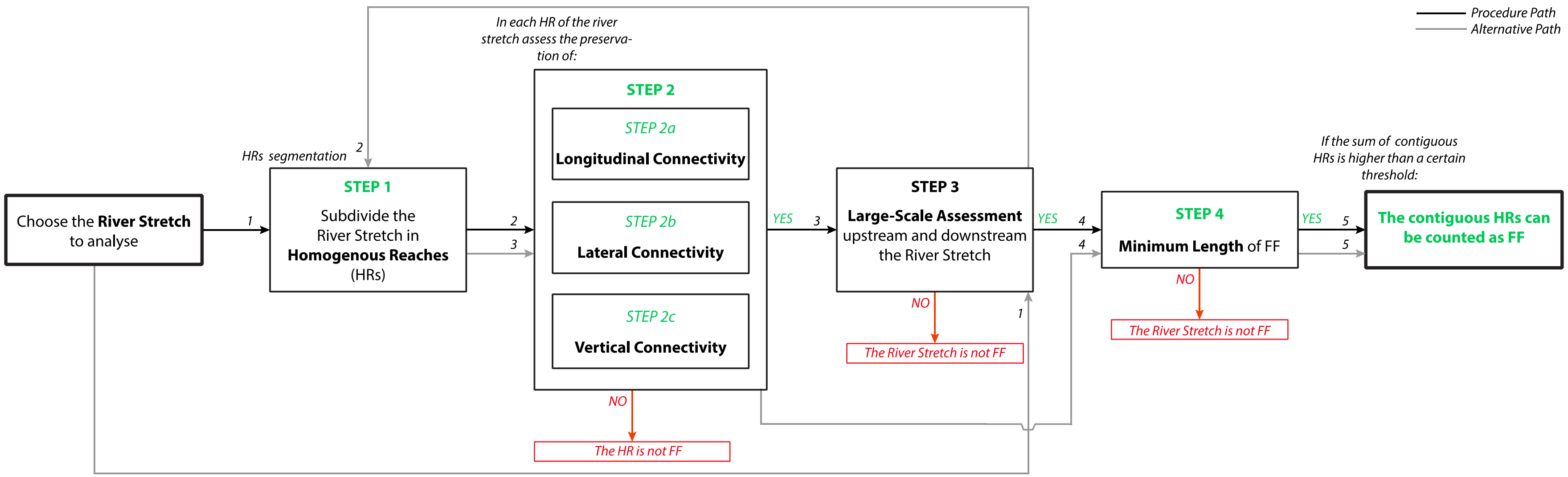
Step 3 addresses the limitations to continuity outside the (potential) FFR stretch (consisting of one or more adjacent homogeneous reaches), both upstream and downstream.

Step 4 verifies whether the (potential) FFR stretch has sufficient length for the typical ecological and hydromorphological processes to take place.

All steps need to be considered before concluding that a river stretch is free-flowing, but it is not necessary to follow the steps in strict order. In some cases, it may be more useful to proceed with Step 3 before Step 2, especially when the users are aware of strong limitations to continuity outside the reach under investigation, which could entail that the reach, in any case, cannot be considered free-flowing. To this end, the schematic overview in Figure 1 indicates a procedure path and an alternative path.

[1] https://amber.international

Figure 1 - Schematic overview of the different elements of the procedure to evaluate whether a river stretch the criteria to be a FFR. Steps 2a, 2b, 2c, and 3 are more or less independent and can be carried out in any order.



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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 analyses, on which Step 2 will be applied in the following assessment framework. The key requirement for a homogeneous reach is that it allows to apply the methods in step 2 in a coherent way. The length of HRs may vary and usually it is equal to 10 - 100 times the average bankfull width of the river stretch (Gurnell et al., 2014; Rinaldi et al., 2016). Within a HR, current boundary 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). Such conditions determine a homogeneous channel morphology and, consequently, a typical assemblage of geomorphic units, thus of riverine habitats.

There are several possible methods to identify homogeneous reaches. Some Member States have already identified homogeneous reaches using, for example, their WFD hydromorphology assessment methodology and may simply use these as HR (i.e. ISPRA, 2016; CEN, 2020; Gurnell and Grabowski, 2020). Rapid assessment criteria can also be used (e.g. identifying dams/retention weirs as endpoints of a stretch; subdividing the stretch when significant changes in slope and/or discharge occur and when channel morphology changes, etc.).

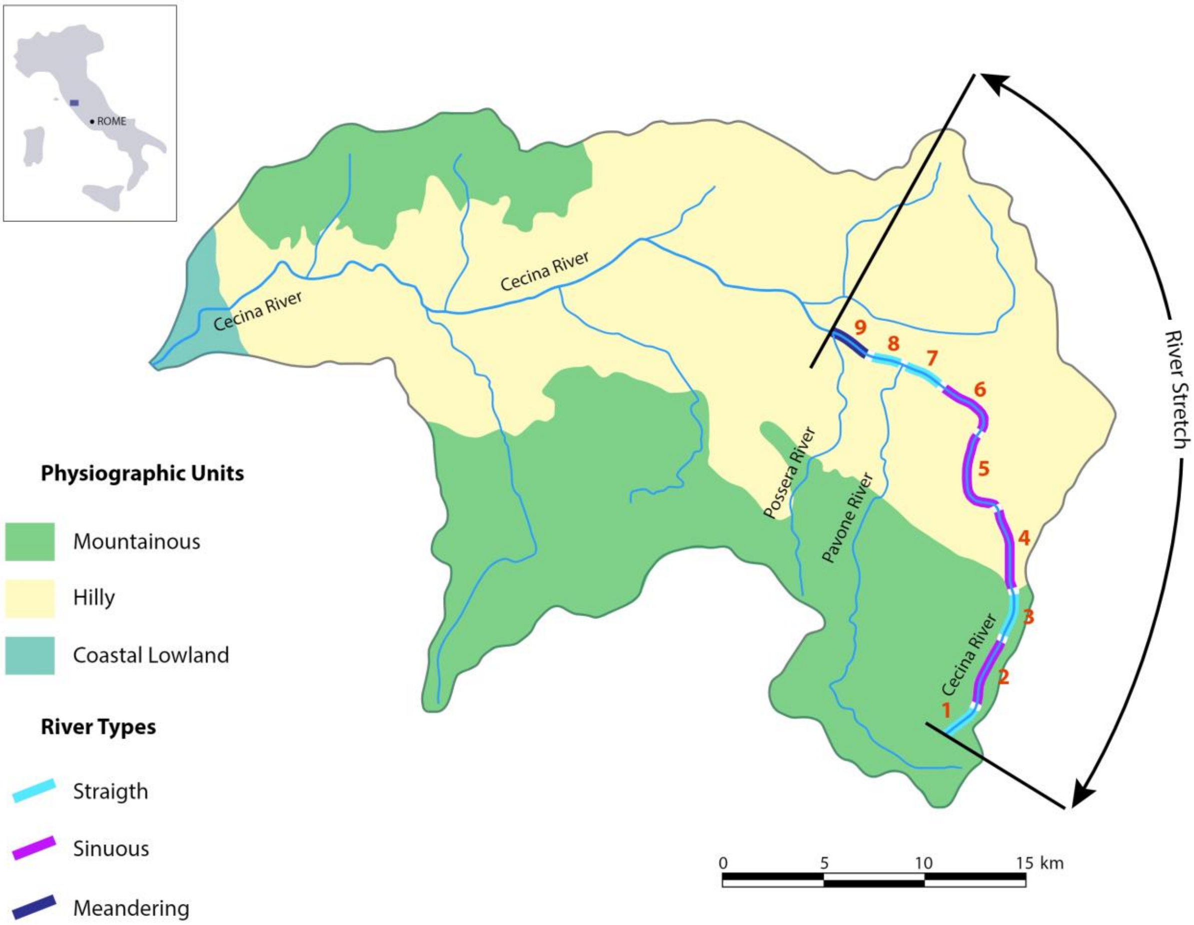
For the purpose of this procedure, the minimum characteristics to be considered to identify a homogeneous reach are the following:

- a homogeneous reach 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 reach (e.g. confined, partly confined, and unconfined), and there should be no permanent major natural barriers (e.g. lakes, waterfalls) within a homogeneous reach.
- there should be no major change in the average bankfull width.
- the reach should be homogeneous regarding the reference fish community.

Besides the above characteristics, the following should be kept in mind when defining homogeneous reaches:

- 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 in two different reaches.
- in case barriers to longitudinal connectivity are found within an identified homogeneous reach, it is possible to segment that homogeneous reach into smaller reaches.

Figure 2 - Segmentation of the Cecina River stretch in nine homogeneous reaches is identified. 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 in homogeneous reaches. 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 homogeneous reaches 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 homogeneous reaches 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 homogeneous reaches 7 and 8. Finally, the homogeneous reaches 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 homogeneous river reach is ensured.

3.2.1 Step 2a – Addressing longitudinal connectivity

The longitudinal connectivity of riverine systems allows the upstream and downstream movement of biota and the continuity of energy flows and matter transfer (water, sediments, nutrients) from upstream to downstream stretches, facilitating and ensuring the existence of a mosaic of riverine habitats connected to each other all over the basins. As a result, the lack of longitudinal connectivity will directly impact those flows and matter transfers. The loss of longitudinal connectivity could be assessed through different indicators, including habitat diversity, aquatic communities (e.g. fish, macroinvertebrates, plants), water quality, sediments.

The analysis consists of three distinct checks:

— Fish mobility check: The first step is to assess whether, by considering the reference conditions, a native fish community is expected in the homogeneous reach under consideration. Indeed, especially in steep mountain streams or temporary rivers, fish communities could be naturally absent, hence implying that in those circumstances the longitudinal connectivity for fish should be overlooked in the assessment. Information regarding the reference fish community in the reach under consideration can be acquired either through previous plans/studies/reports concerning the river itself or from the scientific literature. In the absence of reports and/or scientific data, estimation of the reference fish community structure should be conducted based on the expert opinion, based on the structure of fish communities on similar river stretches.

  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 homogeneous reach needs to be verified. Any artificial structure that is permanently 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 and Baran, 2012; Baudoin et al., 2014; Kreutzenberger et al., 2020; Nielsen & Szabo-Meszaros, 2022). A barrier mitigated by a fish pass within the homogeneous reach is not considered to allow the permanent and unaided passage of fish, and thus it is considered as a barrier, hindering the full connectivity of the river stretch. These structures usually only restore fish passage partially and/or only for some species/age stages.

  If in the reference conditions, a native fish community is not expected to be present in the reach (even if fish species are present e.g. due to stocking) the analysis consists of only the two following checks, as the criterion on fish is not relevant.

— Sediment transport check: absence in the homogeneous reach of any barrier that significantly alters sediment transport. To perform this check, the users can refer to consolidated procedures set out in the relevant literature (e.g. MQI methodology, see Rinaldi et al., 2016). In Annex 2 there are indications of possible barrier types that can be considered negligible in obstructing sediment transport. However, and if feasible, it is advisable to implement a specific study site verification.

— Ecological flow and hydrological alteration check: an ecological flow must be guaranteed during the whole year (EC, 2015) in the whole reach. In particular, the residual hydrological alterations must not determine non-natural physical disconnections within the homogeneous reach, 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 homogeneous reach is considered to fulfil the free-flowing criterion for longitudinal connectivity.

3.2.2 Step 2b - Addressing lateral connectivity

Box 1 - Overview of abbreviations used in Step 2

L_{tot}: total length, meaning the sum of the lengths of <u>all</u> lateral barriers (attached and non-attached to the riverbanks) located in the corridor.
L_{att}: sum of the lengths of <u>attached</u> lateral barriers located in the corridor.
p: multiplying factor used to compute the width of the corridor where lateral connectivity assessment is taking place. It takes different values depending on the river type.
C: width of the corridor (starting from each riverbank) where lateral connectivity assessment is taking place. $C = pW$.
L_c: length of the homogeneous reach assessed.
W: average bankfull width.

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.

In order to assess the lateral connectivity of the homogeneous reach 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 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, as due to the presence of urbanisations and infrastructures 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 in the HR. The assessment corridor can be delineated by multiplying W by a factor p, which depends on the river type (Brierley and

Fryirs, 2013). The distinction between single-thread, transitional, braided and anabranching river types 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;

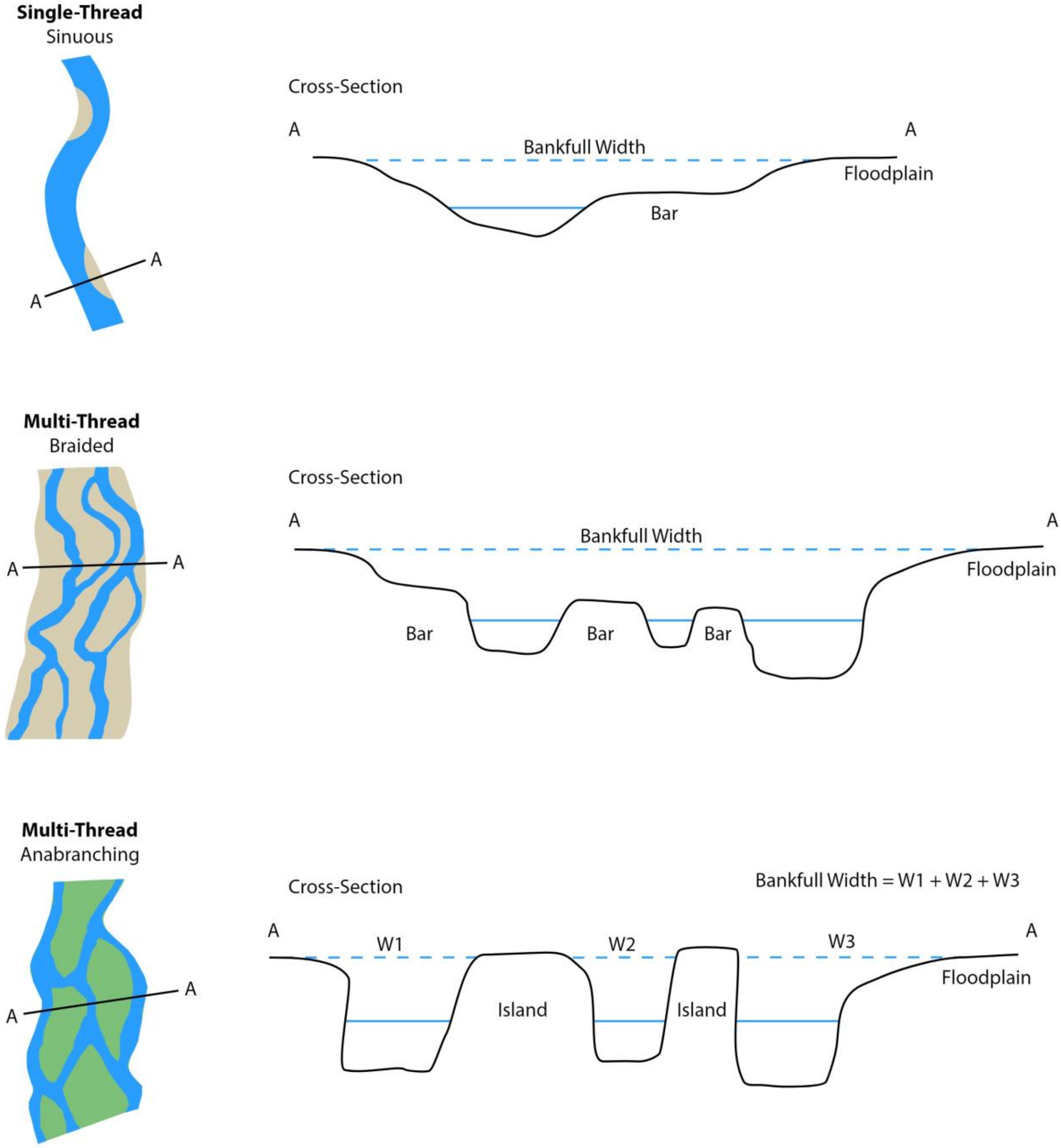
— $p = 0.1$ for braided rivers.

The bankfull width W to use in this computation is the average value in the homogeneous reach, under 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 homogeneous reach 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 are 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 itself, i.e. imposing a low $p$value.

Figure 3 helps in defining the bankfull width for different river types, namely single-thread (sinuous) and multi-thread (braided and anabranching). For the other types of single-thread rivers (straight, meandering), the identification is straightforward, while 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 simply $C = pW$ 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 4, left panel). It is also possible to draw the corridor from the centerline of the river, rather than from the riverbanks. If so, the formula is: $C = pW + 0.5W$ (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 these cases, the floodplain approach would be the most adequate to delineate the fluvial corridor for the assessment.

Figure 3 - Identification of the bankfull width in different river types. The water surface refers to normal water channel conditions (plan view on the left and continuous light blue line on the right) or bankfull conditions (dashed light blue line on the right).



Source: created by the authors

Anabranching rivers are a particular case, where the single channels are divided by islands, thus representing part of the floodplain. Hence, the bankfull width W for anabranching rivers is the sum of the bankfull widths of each individual channel (Figure 3). Then the assessment corridor is drawn starting from the outermost channels on both sides of the river. Therefore, the procedure considers all the lateral barriers within the boundaries of this external buffer, thus including all the channels and the islands in between (Figure 4).

It may happen, especially with small rivers, that the riverbanks are partly covered by vegetation, by slopes or that the quality of the image does not allow them to be distinguished precisely. In these particular cases, we can rely on an expedited procedure for defining the width to be used for the delineation of the river corridor. In particular, it is possible to define bankfull width classes (e.g., 1-5 m, 5-10 m, etc.) if the precise average width of a homogeneous reach is not known. In this case, the upper limit of the width class is used for the fluvial corridor identification (e.g. if the width class is 5-10 m, 10 m is used to define the fluvial corridor), except for large rivers (average bankfull width >50m), where the identification of the bankfull width from images is mandatory.

If the width of the corridor calculated as above exceeds the width of the floodplain (e.g. in narrow valleys, or for river reaches that are partly confined by the valley slopes), then the evaluation corridor coincides with the floodplain and only lateral barriers within the floodplain are considered.

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:

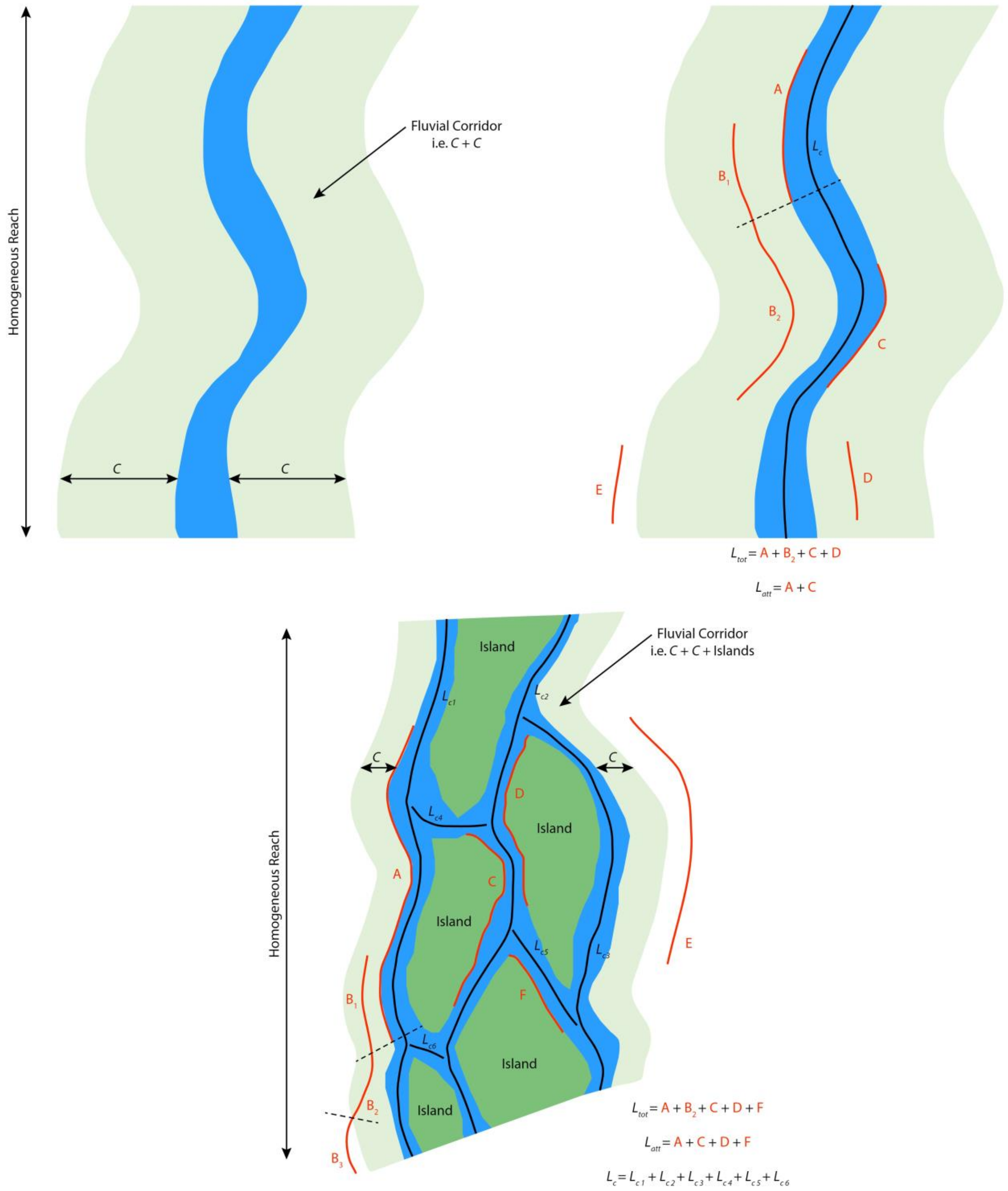
- The presence of residential settlements, roads or railroad tracks is usually associated with some type of bank protection.
- Flood maps corresponding to different return periods (e.g. 10- and 100-years) can be used to highlight the presence of levees, embankments or, conversely, natural confinement (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.

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 4). If two barriers on the same side overlap (e.g. presence of an attached bank defense 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 the 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 of the presence of lateral barriers must be done considering each single channel.

Figure 4 - Identification of the fluvial corridor and deriving the length of the homogeneous reach (L_c), of the total length of the lateral barriers (L_{tot}), and of the total length of the attached lateral barriers (L_{att}) for different river types.



Source: created by the authors

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

Note: these criteria are a first recommendation based on expert judgment, but the multiplication factors (0.1/0.2/0.4) need to be confirmed and possibly revised based on other examples/case studies. A sensitivity analysis will be required. 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 bankfull width W within the homogenous reach (see Figure 3).

— Measure the 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 4):
 - 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.

This criterion mandates that the presence of artificial impermeable surfaces is allowed for a limited length of the HR, specifically less than 5% of the length L_c of the homogeneous river reach. This ensures that their presence minimally affects vertical connectivity and riverbed composition (Rinaldi et al., 2016). Artificial impermeable surfaces are typically associated with bank protection structures and bed revetments (see Annex 2). In some circumstances, the presence of cumbersome fords present in the same HR can produce the same effects on vertical continuity. 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 cadaster of hydraulic works, if available, refer to pre-existing studies, or implement ad-hoc surveys.

In case where the extension of fords or other artificial impermeable surfaces exceeds 5% of L_c, then the HR cannot be considered free-flowing.

3.3 Step 3 - Large-scale assessment of upstream and downstream off-site pressures

In addition to the examination of the lateral, longitudinal and vertical connectivity of the homogeneous reaches 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 hindered by upstream or downstream pressures.

This large-scale assessment can also be carried out independently from the previous steps, e.g. as part of an initial screening exercise identifying candidate free-flowing river stretches (Figure 1).

The proposed 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, downstream 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.

3.3.1 Upstream off-site pressures (sediment load)

To understand if the river stretch under investigation is affected by a substantial reduction of the upstream sediment load, the analysis should be focused on the following steps:

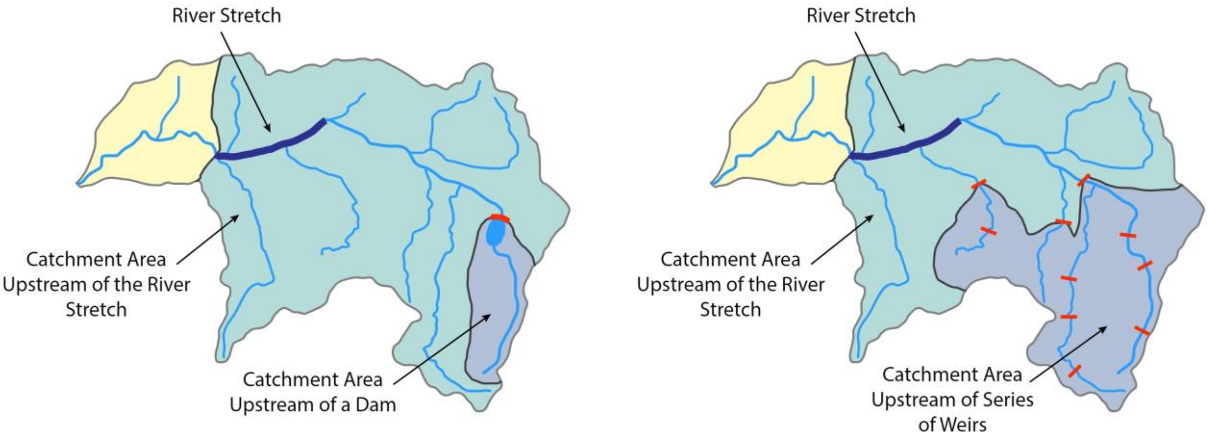
1. Confirm whether there are barriers upstream the river stretch that could significantly reduce the sediment load and connectivity downstream. If there are no barriers or only barriers that have no significant impact on sediments (based on barrier type, see Annex 2), the upstream continuity can be considered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

2. If a study is available assessing the geomorphological behaviour of the HRs within the river stretch and this excludes relevant morphological alterations, such as change of morphological configuration, ongoing channel narrowing/incision, significant alteration of sediment granulometry, then it can be concluded that the upstream barriers have a negligible effect, therefore the upstream continuity can be considered fulfilled. Conversely, if the available studies, taking into account the mitigation measures that are implemented at the existing barriers, if any, conclude that there are significant alterations due to these barriers, the upstream continuity is not fulfilled, thus the reach cannot be assessed as free-flowing.

However, most often, such geomorphological studies are not available, therefore the adoption of suitable proxies becomes necessary to assess the upstream pressure. In case 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, as in most of the cases, such data is not available, the suggested proxy is the percentage of the upstream catchment surface intercepted by relevant barriers (Figure 5). If barriers intercept **less than 30%** of the catchment upstream of the river stretch (calculated starting from the lower end of the river stretch, see Figure 5), the condition on upstream continuity is considered fulfilled (ISPRA, 2016; Rinaldi et al., 2016). 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 (Figure 5).

Figure 5 - Example of how to consider and compute the severity of barriers' sediment load interception in the case of (left) a dam and (right) a series of weirs



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.

3.3.2 Downstream off-site pressures (fish migration)

As a general principle, there should be no 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.

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. Relevant barriers are all downstream barriers (for diadromous species) or all barriers within the migration range (for potamodromous species).

However, there are exceptions to this rule to keep the free-flowing 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 regard 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:

- where, for the time being, it is not technically possible to mitigate at least one of the barriers downstream (for example the Iron Gate on the Danube);
- 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);
- when the mitigation of at least one of the barriers downstream would have negative impacts on the wider environment (for example, fostering the spreading of invasive species);
- 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).

3.4 Step 4 - Minimum length of Free-flowing Rivers

Once the procedure in Steps 2 and 3 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 sustainable populations of native fish species. 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 the same river are considered, while tributaries are computed separately.

If the HRs assessed have fish in reference conditions, then both the minimum length thresholds described below need to be fulfilled (i.e. the maximum between the two values, for the specific river type and width, applies; in the initial proposal developed in the following, in practice the threshold related to fish prevails in most cases). If no fish is expected, then only the minimum length to support typical morphological patterns applies.

The following paragraphs describe proposals for minimum length, based on scientific literature, taking into account both morphological and ecological criteria.

3.4.1 Minimum length to support typical morphological patterns

As previously discussed, the concept of free-flowing rivers implies that sufficient space is ensured for the development of typical fluvial processes. Concerning morphological ones, 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 of the specific river type (e.g. gravel bars, meanders, etc.). Morphological patterns and associated structures exhibit a certain regularity and scale with the width of the channel. Their distance can be predicted by empirical formulae coming from the observation of a great number of rivers or theoretical approaches (e.g. Yalin, 1992; Hundey and Ashmore, 2009; Leopold et al., 2020). The minimum length for FFR can thus be set, according to river type and the average bankfull width, in order to allow a minimum number of repetitions of the expected morphological pattern. Similar approaches underpin river morphological segmentation for morphological evaluation and classification (e.g., according to Gurnell et al. (2014), “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 straight or low sinuosity single channels, Yalin (1992) derived theoretically that the length L between successive alternating bars is approximately 6 times the width of the river:

$$L = 6W$$

For braided rivers, Hundey and Ashmore (2009) derived an empirical estimate for the confluence-bifurcation length L of 4-5 times the channel width:

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

For meandering rivers, the meander wavelength L can be predicted by (Leopold et al., 2020), taking into account that the river length scales with sinuosity P:

$$L = P10.9W^{1.01}$$

By applying these formulae (having assumed a sinuosity equal to 2 for the meandering rivers) and amplifying the results by a factor of 2 (in order to have at least 2 repetitions of some morphological patterns to enable the formation of fluvial habitats), we can retrieve a ‘minimum length’ useful for our scope (see Table 1).

It is important to note that the lower values are set equal to 1000 m. This is considered a minimum target (e.g. in restoration actions). On the other hand, the upper values for meandering rivers and multi-thread rivers are set equal to 20000 m and 5000 m, respectively. In this case, these limits are dictated by the following considerations: i) in wide rivers the fluvial habitats are spatially distributed not only along the longitudinal direction of the river but also transversally, so it is not necessary to reach excessive lengths to appreciate a vast heterogeneity of habitats; ii) very high minimum lengths would not be realistic and thus miss the purpose of the FFR concept.

Table 1 - Minimum length for different river types based on river morphological considerations ensuring a double repetition of typical morphological patterns enabling the formation of fluvial habitats. The values reported in blue also take into account other considerations (e.g. economic and feasibility issues).

Bankfull width (m)	**Meandering rivers (m)**	**Straight or Sinuous rivers (m)**	**Multi-thread rivers (m)**
5	1000	1000	1000
10	1000	1000	1000
20	1000	1000	1000
50	2300	1000	1000
60	2700	1000	1000
100	4600	1200	1000
150	6900	1800	1300
200	9200	2400	1700
250	11500	3000	2200
300	13900	3600	2600
350	16200	4200	3000
400	18500	4800	3400
450	20000	5400	3800
500	20000	6000	4200
550	20000	6600	4600

600	20000	7200	5000
650	20000	7800	5000
700	20000	8400	5000
750	20000	9000	5000
800	20000	9600	5000
850	20000	10200	5000
900	20000	10800	5000
950	20000	11400	5000
1000	20000	12000	5000

Source: created by the authors

3.4.2 Minimum length to support sustainable populations of typical fish species

To support functional connectivity of sustainable fish populations, a free-flowing river must provide sufficient area to guarantee at least a minimum size of meta-population for the type-specific fish community. The required extent, spatial location, and connectivity of the sub-habitats for individual species and life cycle stages must be considered (rearing and growth, spawning, nursery, feeding, hiding, etc.). Thus, the minimum length of a free-flowing river is a complex concept that depends on various factors and can vary significantly depending on the context and the specific criteria used for its definition.

At this stage of development of the method, a preliminary approach is suggested to determine the minimum length of free-flowing homogenous river stretches (contiguous homogenous reaches) relating to typical fish species. As a starting point, minimum values of 5, 10 and 15 km for small (width <10 m), medium (width 10-50 m), and large (width >50 m) rivers are suggested. The required length increases with the size and complexity of river types, mainly depending on the given width class (see Table 2). This is a highly simplified preliminary proposal that will be refined based on a sensitivity analysis of an adequate number of case studies and additional scientific results.

Table 2 - Minimum length for free-flowing river relating to typical fish species

River size	Width class	FFR minimum length
Small	<10 m	5 km
Medium	10 – 60 m	10 km
Large	>60 m	15 km

Source: created by the authors

A more promising, but still mostly untested method to achieve an ecologically meaningful minimum length is based on a concept of macrohabitats and stream order. Further details of this approach are provided in Box 3 and Annex 3.

Box 3 - Proposed approach for minimum length to support sustainable populations of fish based on macrohabitats and stream order

Parasiewicz et al. (2023) classified Europe's rivers into 15 Fish Community Macrohabitat Types (FCMacHT), which offer habitat conditions supporting specific community structure, which is defined as expected proportions of 11 native habitat use guilds. This information is publicly available as a GIS dataset (https://doi.org/10.6084/m9.figshare.22730897).

Hence, a continuous river section assigned one FCMacHT can be considered a homing range of a meta community. However, literature frequently identifies correlations between the Strahler's Stream Order and a shift in the fish community (Barilla et al., 1981; Beecher et al., 1988; Lee et al., 2010). Therefore, despite that it was already one of the attributes used in defining FCMacHT, in this approach it is proposed to strengthen the influence of this factor by including it as a second criterion for identifying a functional unit. Thus, the proposed approach is to determine the functional unit of free-flowing river by combining these two sub-criteria (macrohabitat types and Strahler's Stream Order).

To determine a minimum length of a functional unit that maintains the meta-population we reached out to the "Aichi Targets" as defined in the Strategic Plan for Biodiversity, and Target 11 specifically, which calls for protecting 17% of inland waters to effectively conserve biodiversity. (https://www.cbd.int/doc/strategic-plan/targets/T11-quick-guide-en.pdf).

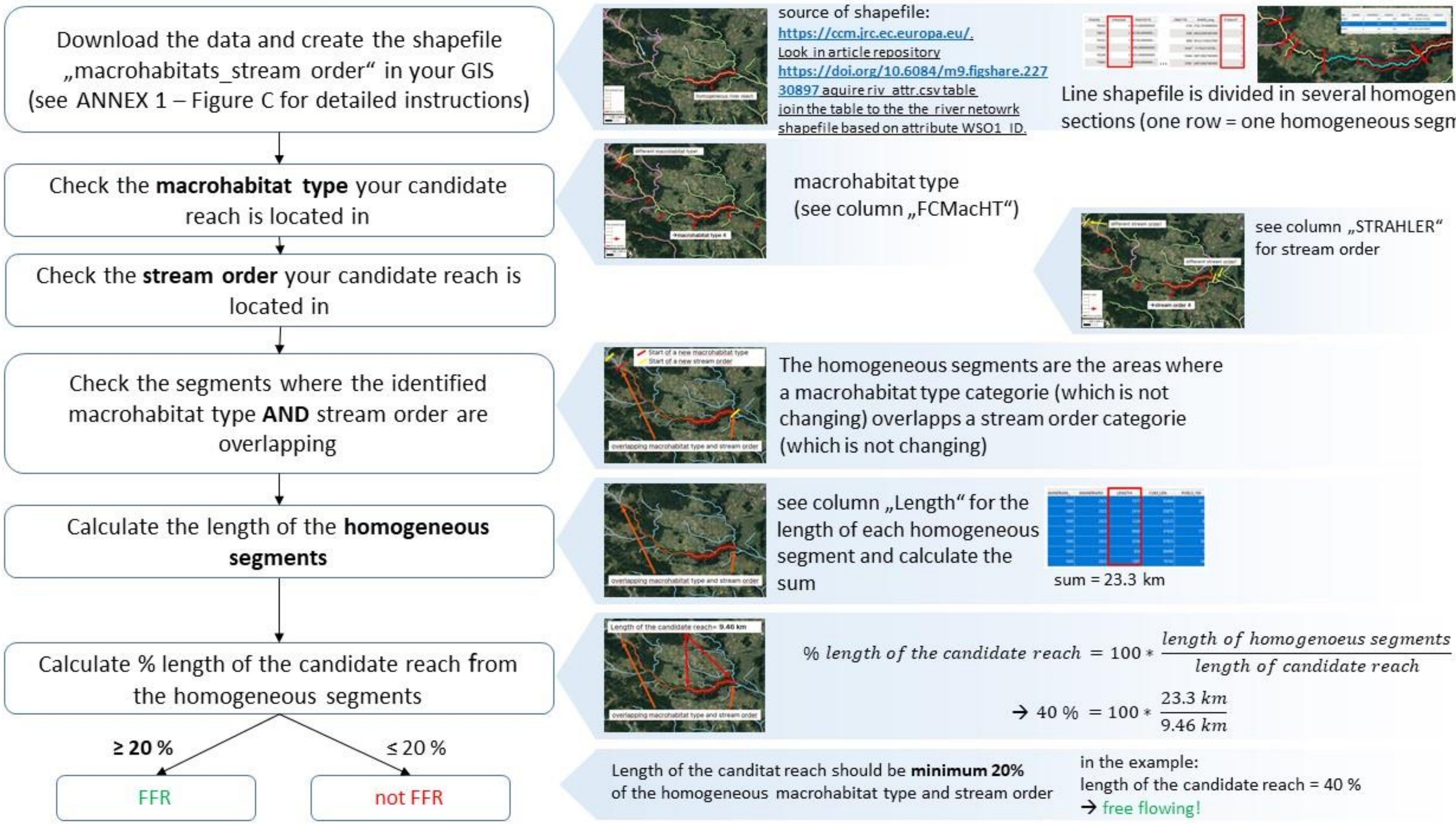
After rounding up the minimum length of free flowing river is defined as 20% of the functional unit i.e. river section continuously expressing one FCMacHT and one Stream Order. See Box 3 and Annex 3 for further details.

Hence, to find the length of a functional unit the user first needs to identify in the stream network the length of a continuous and connected river section encompassing the candidate reach and being assigned the same macrohabitat type and one stream order (see Figure 6). To assure that the candidate reach passes the minimum length criterion, the user needs to verify that the length of the candidate reach is more than 20% of the length of the functional unit.

This conceptual proposal still needs to be verified with available biological data and a sensitivity analysis with an adequate number of case studies. To simplify the application an automated functional unit selection procedure can be developed. For pragmatic reasons the minimum length criterion of free-flowing rivers should be applied not including the tributaries of candidate rivers, however, access to them should be maintained.

More detailed stepwise instructions for this approach can be found in Annex 3.

Figure 6 - Flowchart for a proposed approach to derive minimum free-flowing river length based on fish macrohabitats and Strahler order



Source: created by the authors

4 Conclusions and next steps

The methodology presented in this report makes it possible to identify free-flowing river stretches, focusing on longitudinal, lateral and vertical connectivity both within the river stretch and the catchment scale. It contains different criteria or steps addressing the different aspects 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 find out what needs to be done for the river stretch to achieve free-flowing conditions, or if this is not possible to improve the connectivity. 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.

The authors of this report have tested the methodology in a small number of case studies demonstrating the feasibility of the approach and identifying areas that require further work (e.g. to establish ecologically relevant minimum length criteria). Further testing in a larger number of case studies covering all relevant river types and geographical regions is recommended to further refine the methodology.

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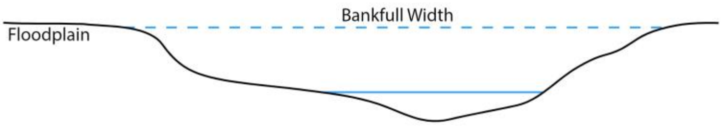
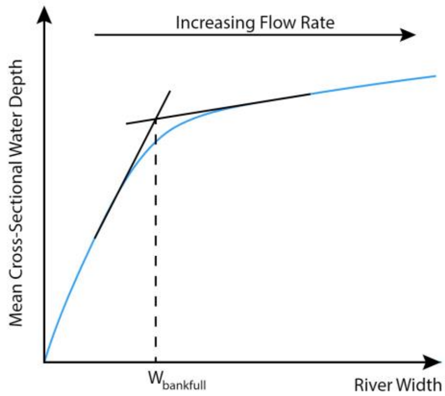
Definitions

For the purposes of this work, as terms of reference ensuring coherence in all the steps of the proposed methodology, 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 that divide the flow into several branches in bankfull conditions. Unlike braided rivers, in which in bankfull conditions the bars are completely submerged, hence the river loses its multi-thread characteristics (except where islands are present), in the case of anabranching rivers the pattern remains multi-thread even in bankfull conditions. The characterizing parameter is the anabranching index which 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, are 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 (WSD 2000). Figure 7 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 7 right panel).

Figure 7- Illustration of bankfull conditions. On the left, the cross-section of a single channel river and its free surface in low water channel (continuous light blue line) and bankfull conditions (dashed light blue line). On the right, a quantitative way to define the bankfull width.





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- Complex barrier: 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 have to be assessed on a case-by-case basis as they are difficult to generalize.

- Confined and unconfined river: 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).

- Diadromous fish species: 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).

- Ecological flows: 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). (CIS Guidance 31; EC, 2015)

- Fish mobility: 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: According to the document “Biodiversity Strategy for 2030 – Barrier Removal for River Restoration” (EC 2022), a FFR 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 free-flowing river 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 discharges, and (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 classes 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 (and in any case lower than 1.5).

— Migratory fish species: Migratory fish are defined according to the 1979 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.

— Potamodromous fish species: Migratory fish that spend their whole life cycle in freshwater but migrate over, sometimes, considerable distances (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 into 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).

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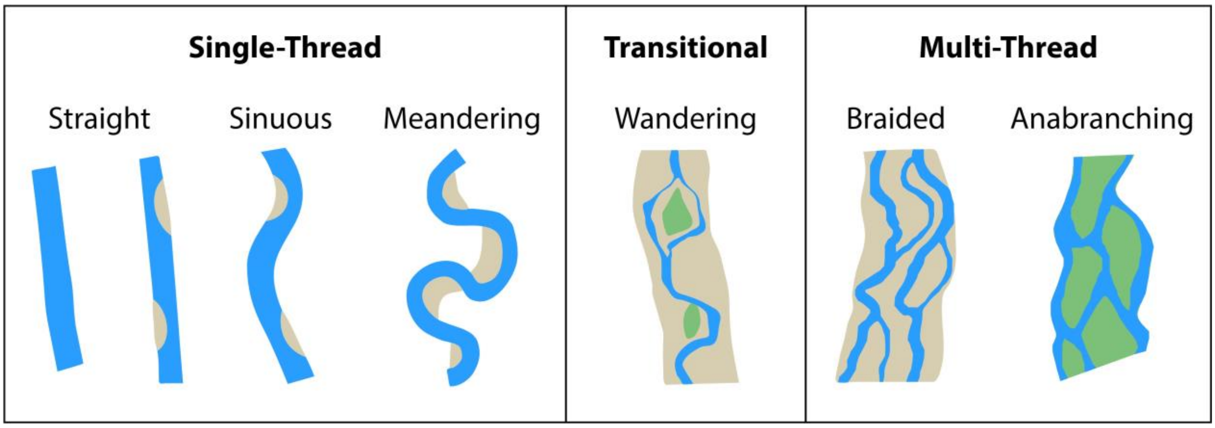
Annex 1. River types considered in the free-flowing rivers procedure

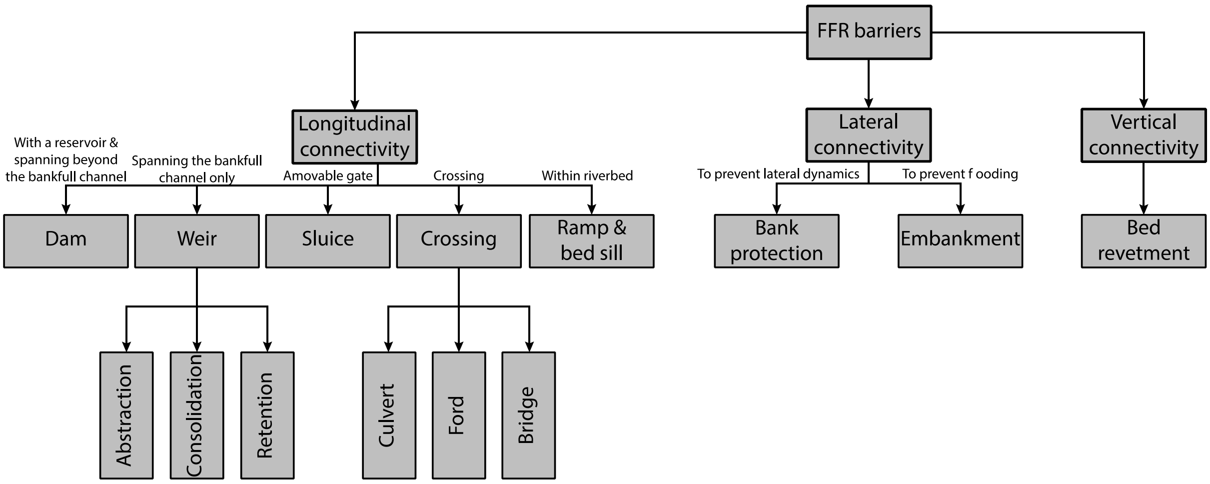
Figure 8 - River type



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



Source: created by the authors

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; 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 the corridor available for 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). Groynes, in some cases, can have a non-negligible effect also on longitudinal connectivity for sediments.

Use: protection against erosion and lateral dynamics.

Impacts on longitudinal/lateral/vertical connectivity

Lateral connectivity is always to be considered (hindering lateral mobility is the main objective of bank protection structures).
Groynes protruding within the water channel can also affect the sediment transport regime; this effect can usually be considered negligible within the scope of the FFR procedure, but this needs to be assessed case by case.

No relevant effects on vertical connectivity.

Pictures

Gabions

Bank wall

Bioengineering bank stabilisation

Groynes

Image sources: Gabions and bank wall: Andrea Goltara, groynes: Google Earth; bioengineering bank stabilisation: 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.

Impacts on longitudinal/lateral/vertical connectivity

Lateral connectivity is always to be considered.

No relevant effects on longitudinal and vertical connectivity.

Pictures

Earthen levees

Bank-edge levees

Bank walls with the function of lev-ees

Image soures: left and right: Andrea Goltara; centre: Rinaldi et al. (2016).

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. Dams block the flow of water and raise the water level, forming a reservoir or an impounded river segment upstream. Sediments can be completely or partially blocked, depending on the dam structure and management. Dams can be of many forms and types, e.g.: gravity dams, arch dams, buttress dams.
Use: water supply, flood retention, and hydropower generation.
Impacts on longitudinal/lateral/vertical connectivity
Longitudinal connectivity is always to be considered. Typically no direct effects on lateral and vertical connectivity, but to be assessed case by case.
Pictures

Gravity dam (left) and arch dam (right)

Image sources: left: AMBER Consortium 2020; right: Andrea Goltara.

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. 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.

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. Abstraction weirs can also be associated with spillways for flood protection purposes. Weirs can have movable elements. In some cases, temporary transversal structures are built within the riverbed, with local bed sediments, to deviate the flow towards an abstraction canal. These are temporary structures (removed by flood or dismantled periodically), usually removed during flood events, thus with limited impact on sediment transport, but their impact on fish migration may be relevant.
Use: regulation of water levels to allow water abstraction
Impacts on longitudinal/lateral/vertical connectivity
Longitudinal connectivity is always to be considered, but its relevance in relation to sediment transport and fish mobility needs to be assessed case by case. Typically no direct effects on lateral and vertical connectivity.
Pictures

Top line: (left) abstraction weir with an abandoned mill; (centre) abstraction weir associated with an Archimedean screw hydropower plant; (right) Abstraction weir with movable gates.

Temporary diversion structure made with loose bed sediments

Image sources: top line: Jones et al. (2021), Andrea Goltara, Google Earth; bottom: Andrea Goltara.

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

Definition

Consolidation weirs aim at reducing the channel slope, thus stabilizing the channel bed. Depending on their size and type they can also intercept the bedload, at least temporarily. When totally filled by sediments on the upstream side, they still influence the sediment transport regime, due to the altered slope, but they have limited effects on the longer-term sediment balance. Consolidation weirs can be composite structures, associated with downstream sills/paved sections to reduce erosion and often occur in series (stepped weirs).

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

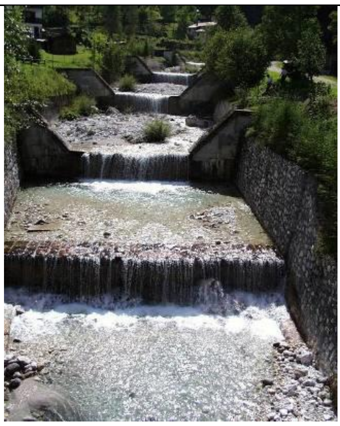
Impacts on longitudinal/lateral/vertical connectivity

Longitudinal connectivity is always to be considered, but its relevance in relation to sediment transport and fish mobility needs to be assessed case by case;

Typically no relevant effects on lateral connectivity (but a series of weirs may be associated with bank protection structures, to be assessed separately).

Impacts on vertical connectivity can range from negligible to relevant, in connection to the presence and extension of bed erosion control structures, to be assessed case by case.

Pictures



Series of consolidation weirs

Consolidation weirs that are totally filled with sediments on the upstream side

Image sources: left: Rinaldi et al. (2015); right: Andrea Goltara.

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

Definition

Retention weirs, also called check-dams, typically located in mountain areas, are 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.

Impacts on longitudinal/lateral/vertical connectivity

Longitudinal connectivity is always to be considered, but its relevance in relation to sediment transport and fish mobility strongly depends on the design/type and needs to be assessed case by case; typically no relevant effects on lateral connectivity (but may be associated with bank protection structures, to be assessed separately).
Impacts on vertical connectivity that can range from negligible to relevant, in connection to the presence and extension of bed erosion control structures, to be assessed case by case.

Pictures

Retention weir

Selective retention weir associated to two consolidation weirs downstream

Selective retention weir with negligible impact on longitudinal connectivity for fish

Image sources: top: Andrea Goltara; bottom: Autonomous Province of Bolzano (HyMoCARES Project).

Type	**SLUICE /LOCK GATE**
Sub-type	**X**

Definition

Sluice is used in the context of this report to define a barrier with one or more movable gates, allowing it to regulate the water level upstream and/or the flow of water in a channel. If the aim is to allow ships/boats to navigate obstructions that create uneven levels of water along rivers and waterways, it is usually called “lock” (or lock gate).
Abstraction weir and sluice are often used as synonyms.

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

Impacts on longitudinal/lateral/vertical connectivity

Longitudinal connectivity is always to be considered, but its relevance in relation to sediment transport and fish mobility needs to be assessed case by case, taking into account its design (e.g. whether an associated sill/basement always creates an obstacle) and how the structure is managed (e.g. typically a lock when open can be fully passable both by fish and sediments).
Typically no relevant effects on lateral and vertical connectivity.

Pictures

Sluice associated with an abstraction work

Lock gate for navigation

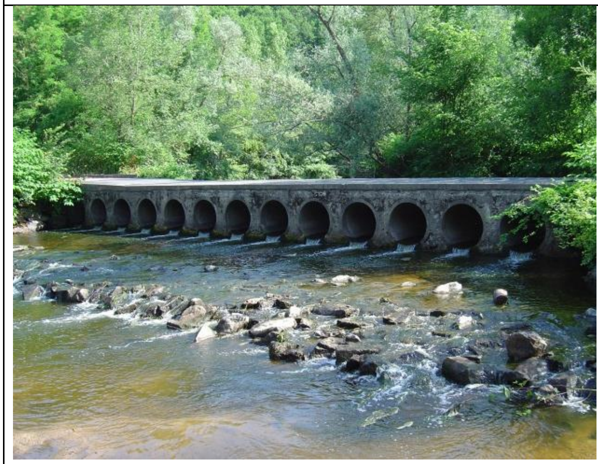
Image soure: Andrea Goltara.

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

Definition
Crossing structures include a broad range of transversal barrier types (see sub-types below)with widely variable impacts on connectivity.

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 tracks or railways). It varies in form from round and elliptical to box-shaped.
Use: carrying a stream or river under an obstruction.
Impacts on longitudinal/lateral/vertical connectivity
Longitudinal connectivity always to be considered, but its relevance in relation to sediment transport and fish mobility needs to be assessed case by case, depending in the size and design of the structure. Negligible impact on lateral connectivity. Local impact on vertical connectivity.
Pictures




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

Image sources: left: OFB 2021; right: Andrea Goltara.

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

Definition

A ford is a low-head channel structure which creates a stable, shallow section for wading the river or stream, that can be submerged at high flow conditions and typically not significantly protruding from the river bed, thus not causing significant alterations in sediment dynamics.

Use: river crossing.

Impacts on longitudinal/lateral/vertical connectivity

Longitudinal connectivity always to be considered, but its relevance needs to be assessed case by case; typically, the impact on sediment transport is negligible, while the impact on fish depends on the design and local conditions.

Negligible impact on lateral connectivity.

Local impact on vertical connectivity.

Pictures

Fords

Image sources: left: OFB 2021; right: Andrea Goltara.

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

Definition

Bridges are crossing structures built over a river, with a wide range of forms and sizes, designed to allow the flow of water below their base. Their interference with the riverbed is widely variable, depending on the design (in particular with or without piles in the riverbed) and height with respect to the bankfull level. Bridges with piles are often associated with bed sills. (REFER TO SILLS IN THE ANALYSIS).

Use: river crossing.

Impacts on longitudinal/lateral/vertical connectivity

Longitudinal connectivity has to be assessed case by case, but in the context of this methodology, it is typically negligible (the effect on wood transport is not considered) unless the bridge is significantly undersized with respect to the bankfull flow level.

Typically, negligible direct impact on lateral and vertical connectivity (but may be associated with other structures determining a significant impact).

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

Image sources: left: Betta et al. (2008); right: 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, loose or cemented with concrete. These are generally low-head structures not protruding significantly outside of the riverbed, but extending longitudinally. Ramps can also be built downstream to or as replacement of sills or weirs as a mitigation measure to improve connectivity for fish.
Use: local riverbed stabilisation
Impacts on longitudinal/lateral/vertical connectivity
The impact on longitudinal connectivity needs to be assessed case by case, but usually the effect on sediment transport is negligible, while the impact on fish mobility depends on the design and local conditions (if the ramp slope and rock size are very close to the natural local conditions, its impact may be negligible). Negligible impact on lateral connectivity. Local impact on vertical connectivity variable and to be assessed case by case (e.g. it may be relevant if the ramp is cemented and its longitudinal extension is significant).
Pictures

Ramp with boulders

Ramp below a sill to facilitate fish passage

Image sources: left: Jones et al. (2021); right: Massimo Pascale.

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

Definition

Bed sills are transversal structures located within the channel, aimed at locally stabilizing the channel bed. Their effect is similar to that of consolidation weirs, but sills are typically low-head structures, built in lower slope stretches, not protruding significantly outside of the riverbed and lacking the wing walls typically included in the weirs structure. Sills are often associated with bridges with piles in the riverbed.
These can also be called "ground sills".

Use: local riverbed stabilisation.

Impacts on longitudinal/lateral/vertical connectivity

Longitudinal connectivity is always to be considered, but the impact on sediment transport can usually be neglected, while the effect on fish mobility needs to be assessed case by case;

Typically no relevant effects on lateral connectivity (but a series of sills may be associated with bank protection structures, to be assessed separately).
Only local impact on vertical connectivity; it can become relevant only in the case of an extensive series of sills.

Pictures

Left column: (top and middle) bed sills associated with a bridge; (bottom) bed sill
Right column: (top) two bed sills connected by a boulder ramp, which impact on connectivity can be considered negligible; (bottom) a series of bed sills

Image sources: left column: Andrea Goltara; right column: Autonomous Province of Bolzano and Andrea Goltara.

Type	**BED REVETMENT**
Sub-type	**X**

Definition

Bed revetments are structures aimed to stabilise the river bed, obtained by covering and/or reinforcing the bed with different materials, e.g. concrete, stone. They can be permeable or impermeable.
The revetment (i.e. the covering or reinforcement) of the riverbed is often coupled with bank protections, aiming to stabilise the channel and diminish the resistance to the flow. This leads to a decrease in water levels and to an acceleration of the current's velocity and consequently the increase of erosive processes. Bed revetment often serves to protect other hydraulic structures from localized erosion, which could undermine their foundations. Examples, very frequent in steep mountain reaches, include bridge piers and the downstream sections of weirs or dam or urban reaches in lowland context to prevent sedimentation.

Use: Stabilise the riverbed, increase river channel conveyance capacity, and prevent sedimentation.

Impacts on longitudinal/lateral/vertical connectivity

Typically, negligible impact on longitudinal connectivity and no direct impact on lateral connectivity, but bed revetment is usually associated with extensive bank protection structures (to be assessed separately).

They have a relevant impact on vertical connectivity, which is typically totally interrupted. Bed revetments cause strong alteration in channel morphology in terms of the disappearance of sediment and related bed forms (loss of habitats) as well as in terms of an alteration of vertical continuity with groundwater (hyporheic zone).

Pictures


Concrete bed revetment in stone (left) and concrete (right)

Image sources: left: Rinaldi et al. (2016); right: Andrea Goltara.

B: 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 are 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…).

C: 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	Article on the extent and effect of road crossing on aquatic ecosystems (UK)	https://esajournals.onlinelibrary.wiley.com/doi/abs/10.1890/120168

expanding inventories of both dams and road crossings. *Frontiers in Ecology and the Environment* 11, 211–217. https://doi.org/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
OFB. Description et champs d'application de la méthode de l'Information sur la Continuité Ecologique (ICE)	Protocol to assess river continuity in France and online application (ROE-ICE)	https://patbiodiv.ofb.fr/fiche-methodologique/continuite-ecologique/description-champs-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
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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

Annex 3. Detailed description of a proposed method to derive minimum length to support sustainable populations of fish based on macrohabitats and stream order

Minimum length criterion can be determined using the fish community macrohabitat types (FCMacHT) developed within the AMBER Adaptive Management of Barriers in European Rivers (EU Horizon2020 Project: AMBER #689682). Open source data and project results can be used to download the database. A procedure to use this publicly available macrohabitat typology is as follows:

- download a dataset of CCM2 that you are interested in from an open access link: https://ccm.jrc.ec.europa.eu/.
- from the article repository acquire riv_attr.csv table
- join the table to the river network shapefile based on attribute WSO1_ID.
- since the European river network's geographic representation may not perfectly fit into national datasets, the user is advised to incorporate the macrohabitat types (and Strahler stream order if not already existing in their dataset) from the European dataset into their data and continue calculations there;
- if in the macrohabitat dataset, there appear to be relatively small reaches of macrohabitat types along a river continuum different from the relatively long stretches of macrohabitats immediately before and after that reach the user is advised to treat these reaches as misclassification. In such a case it seems to be better to use for the small reach the macrohabitat type from the above/below river reach instead.
- Identify functional unit and its length
- Compare the length of candidate reach to the length of functional unit and calculate the proportion.

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