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WPT2. Integrating hydromorphological assessment and management at different scales
D.T2.2.1 “Technical notes on a multi-scale framework for assessing the hydromorphological conditions of Alpine rivers”

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Authors: Mario Klösch, Sebastian Pessenlehner, Roman Dunst, Eddy J. Langendoen, Frédéric Liébault, Andrea Goltara, Johann Aigner, Felix Reebs, Mélanie Bertrand, Helmut Habersack
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CONTENTS

1. Introduction

The alpine rivers are affected by multiple pressures, leading to various ecological and technical problems. Given the transport of water, sediment and wood the problems which emerge along the river course may result from local processes, but also from processes occurring far upstream in the catchment or somewhere along the river network. In river management, especially in river restoration, it is crucial to identify the pressures which cause the observed hydromorphological condition.

In a first step, a questionnaire is conducted among the project partners on the hydromorphological issues they encounter at their case study sites. The survey outcome serves to link observed morphological and biological degradation to causes which may have their origin somewhere in the river network, and to get an overview about the relevance of several anthropogenic interventions for the hydromorphological condition of alpine rivers. These anthropogenic interventions are then to be addressed by the compilation and development of related indicators in the multi-scale hydromorphological framework.

In a second step, the indicators are embedded in an assessment procedure. The hydromorphological assessment considers the anthropogenic interventions, which are effective at various scales.

In the last step, a methodology for the priorisation of restoration measures is proposed, based on the developed assessment procedures and other tools developed in HyMoCARES.

2. Identification of the relevant indicators for hydromorphological condition of Alpine rivers

This chapter serves for identifying the indicators which are relevant for assessing the hydromorphological quality of Alpine rivers. Its focus is on identifying the causes for alteration of the hydromorphological condition, which will then provide a prioritised list of anthropogenic influences which need to be tackled by appropriate indicators in the assessment procedure.

2.1. Identification of causal links of hydromorphology following the DPSIR scheme

To identify appropriate indicators for the assessment of the hydromorphological status in a river it is crucial to understand the causal links between origins and consequences of environmental problems. To evaluate hydromorphological issues of the HyMoCARES case study sites an online survey was developed following the DPSIR (Drivers-Pressures-State-Impact-Responses) Framework (Kristensen, 2004) as illustrated in Fig. 1. This framework provides an integrated assessment for analysing environmental problems and responses with respect to sustainable development (ISPDR, 2015). The DPSIR scheme was therefore selected for a systematic data collection among all case study sites, describing the hydromorphological issues in Alpine Space Rivers. The survey builds the basis for the identification of indicators covering all determined hydromorphological issues.

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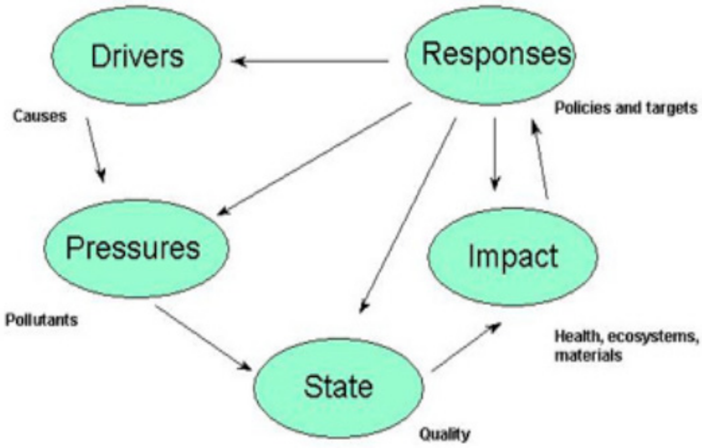

Fig. 1. DPSIR scheme describing a chain of causal links between drivers, pressures, states, impacts and responses (Kristensen, 2004).

2.2. Structure of the DPSIR survey on hydromorphological issues

As the DPSIR scheme is a general approach for all kind of environmental-related problems it was necessary to adapt the DPSIR elements to the hydromorphological issues of Alpine Rivers. Therefore a literature research was carried out to take into account all relevant drivers, pressures, states, impacts and responses on the topic. Hydromorphological issues treated in several evaluation methods and studies were considered such as the Hydromorphological Evaluation Tool (Klösch and Habersack (2017), the Morphological Quality Index (MQI) by Rinaldi et al. (2016), impacts and processes in Alpine Rivers found by Habersack & Piégay (2007), the Global Pressure Index (GPI) developed by Schinegger et al. (2012) as well as national guidelines for assessement of the hydromorphology of rivers (Mühlmann & Mauthner-Weber, 2010).
The resulting elements were implemented in an online survey to evaluate the HyMoCARES case study sites. Within the survey the drivers were divided into 4 groups:

- Sediment and biota connectivity (disconnection)
- Hydrology
- Land use & Water quality
- Morphology

In the DPSIR scheme a ‘driving force’ is defined as a need of humans for exploiting the environment or adjusting it to his interest. In each of the defined groups there are several drivers related to hydromorphology such as hydropower, land use, hazard prevention and the production of raw materials. All of these four groups of drivers represent fields of human interests leading to pressures on Alpine Rivers such as barriers, riparian clearing, river narrowing etc.. As a result of these pressures the state of the rivers changes, which means that the physical, chemical and biological condition are affected. The decreased quality of the state may furthermore lead to an impact on the ecosystem. Degradation of abiotic and biotic factors implies various negative impacts leading to ecologic and economic effects. As a result of undesired impacts responses such as adaptions of environmental policies or restoration projects can affect any part of the causal chain causing a reversal of trend.

The structure of the developed DPSIR scheme online cognitoform survey is depicted in Fig. 2 for the group 'sediment and biota connectivity'. For all of the 5 elements (D-P-S-I-R) in the survey it was possible to select predefined options or to add individual entries. Furthermore, the level of influence on the case study site (little, significantly, highly affected) and the general ranking of the specific pressures have been surveyed.

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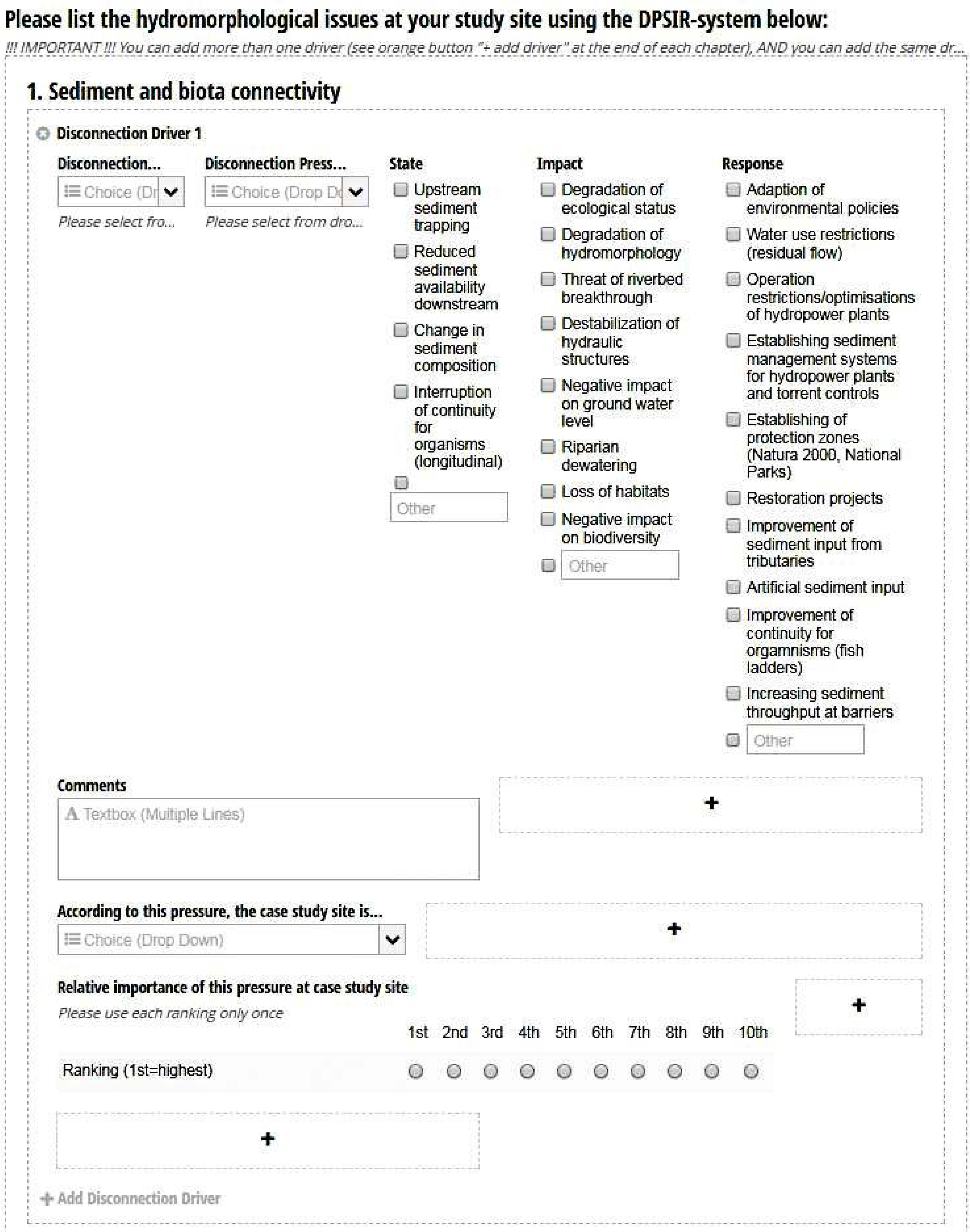

Please list the hydromorphological issues at your study site using the DPSIR-system below:

!!! IMPORTANT !!! You can add more than one driver (see orange button "+ add driver" at the end of each chapter), AND you can add the same dr...

1. Sediment and biota connectivity

Disconnection Driver 1

Disconnection...
Choice (Dr
Please select fro...

Disconnection Press...
Choice (Drop Do
Please select from dro...

State
- Upstream sediment trapping
- Reduced sediment availability downstream
- Change in sediment composition
- Interruption of continuity for organisms (longitudinal)
- Other

Impact
- Degradation of ecological status
- Degradation of hydromorphology
- Threat of riverbed breakthrough
- Destabilization of hydraulic structures
- Negative impact on ground water level
- Riparian dewatering
- Loss of habitats
- Negative impact on biodiversity
- Other

Response
- Adaption of environmental policies
- Water use restrictions (residual flow)
- Operation restrictions/optimisations of hydropower plants
- Establishing sediment management systems for hydropower plants and torrent controls
- Establishing of protection zones (Natura 2000, National Parks)
- Restoration projects
- Improvement of sediment input from tributaries
- Artificial sediment input
- Improvement of continuity for orgamnisms (fish ladders)
- Increasing sediment throughput at barriers
- Other

Comments
Textbox (Multiple Lines)

+

According to this pressure, the case study site is...
Choice (Drop Down)

+

Relative importance of this pressure at case study site
Please use each ranking only once

	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
Ranking (1st=highest)	○	○	○	○	○	○	○	○	○	○

+

+

+ Add Disconnection Driver

Fig. 2. Online form to evaluate hydromorphological issues of the HyMoCARES case study sites following the DPSIR scheme.

2.3. Results of the DPSIR survey on hydromorphological issues

The online survey on hydromorphological issues was spread among all partners of the HyMoCARES project to evaluate the study sites. An overview of these sites is given in Fig. 3. Besides the information following the DPSIR scheme also general information such as hydrological and sedimentological boundary conditions but also ecological and hydromorphological status for each river was gathered and illustrated in Tab. 1.
In total there are entries for 14 study sites considered in the analysis. Maggia is not considered, whereas for both Avisio and Adige there are two entries.

Fig. 3. Location of the HyMoCARES case study sites in the Alpine Space region (http://www.alpine-space.eu/projects/hymocares/en/case-studies).

The overview in Tab. 1 shows that the survey carried out covers rivers of 5 nations in the Alpine Space. The river basins range from rather small areas of a few hundred km² (e.g. Avisio, Pezzé di Moena reservoir, Italy, 211 km²) to much larger basins such as the Slovenian Drava, the Mur river or the Adige at the site Zevio. All of these 3 study sites drain areas larger than 10 000 km². Similarly, the mean discharges of the study sites show a large range between 5.46 m³/s at the Drac River in France and 150 m³/s at the Mur River in Austria. Together with these parameters also other characteristics of the 14 evaluated study sites such as bed slope, river bed width or substrate are showing wide ranges. Therefore, this survey is able to adequately represent the hydromorphological issues in Alpine Rivers.

Tab. 1. Overview of general information of the HyMoCARES case study sites.

Partner	Case Study Site	Site Name	Country	River Basin [km²]	Mean Discharge [m³/s]	1 Year Flood Discharge [m³/s]
IRSTEA	Buëch River	St Sauveur Dam	France	836	14.1	140
IRSTEA	Drac River	St Bonnet	France	340	5.46	41
AdB Adige	Adige	Zevio	Italy	12000	150	800
APC PAB	Adige	Adige	Italy	2495	200	400
PAT	Avisio	Pezzé di Moena reservoir	Italy	211	6	-
PAT	Avisio	Stramentizzo reservoir	Italy	726	8.5	-
APC PAB	Isarco	Isarco	Italy	3579	150	250
APC PAB	Talvera	Talvera	Italy	426	15	40
LFV	Wertach	Wertach vital	Germany	1441	16.4	170
LFV	Lech	Licca liber	Germany	2350	81.2	421
BOKU	Drau	Kleblach	Austria	2445	74	320
IzVRS	Drava	Melje - Ptujsko jezero	Slovenia	13450	38	116
BOKU	Mur	Gosdorf	Austria	10340	150	700
BAW-IWB	Salzach	Untere Salzach	Austria/Germany	6119 (Pegel Laufen), 6655 (Pegel Burghausen)	236 (Pegel Laufen), 250 (Pegel Burghausen)	1130

Partner	Grain Size of Surface Substrate D50 [mm]	Artificiality	Valley Confinement at Site	Ecological Status
IRSTEA	21	restored	unconfined	bad
IRSTEA	40	restored	unconfined	bad
AdB Adige	30	regulated	unconfined	good
APC PAB	20	regulated	unconfined	very good
PAT	30	regulated	partly confined	mediocre downstream - poor upstream
PAT	30	no channel constraints	partly confined	good downstream - mediocre upstream
APC PAB	120	regulated	partly confined	very good
APC PAB	160	regulated	partly confined	good
LFV	-	restored	confined	moderate potential (Wertach is a HMWB and therefor is the ecological potential not status)
LFV	-	regulated	confined	moderate (it is a HMWB so it is potential)
BOKU	25	restored	unconfined	good
IzVRS	45	no channel constraints	partly confined	good
BOKU	35	restored	unconfined	good
BAW-IWB	20.4 (substrate)	regulated	confined	moderate/bad depending on the assessment procedure (FIA in Austria) bzw. (fiBS in Germany)

2.3.1. Drivers

Fig. 4 shows the results for the groups of drivers which were defined in chapter 2.2. From all the mentioned drivers in the survey around 30% are related equally to morphology, disconnection and hydrology. A smaller part of 11.9% of mentioned drivers are related to land use & water quality.

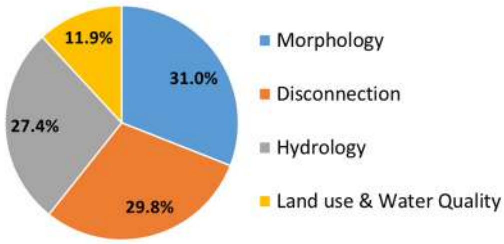

Fig. 4. Deviation of categories of drivers among the HyMoCARES case study sites.

Fig. 5 shows the deviation of drivers among the HyMoCARES case study sites in detail. With 41.7% of the 84 entries in the survey, the survey outcome suggests that hydropower is the most important driving force for hydromorphological issues at the selected alpine rivers. Together with hazard prevention (11.9 %), agriculture (8.3 %) and land use change (8.3 %) these four drivers are suggested to be responsible for ~70 % of hydromorphological alterations.

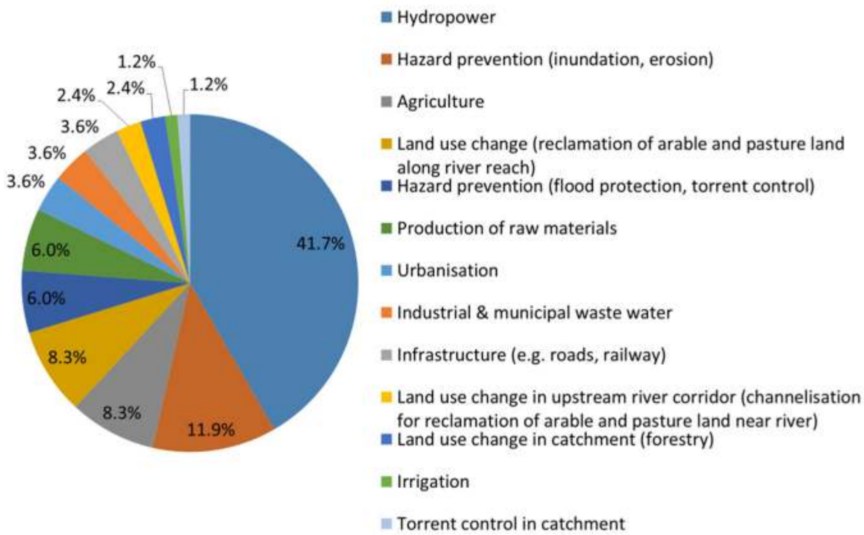

Fig. 5. Relative distribution of drivers among the HyMoCARES case study sites.

2.3.2. Pressures

The next level of the DPSIR-scheme based survey addresses the pressures. Fig. 6 depicts the relation between drivers and pressures. The left diagram shows those drivers, which cause - according to the experts for the case study sites - the most important pressures. The pressures, which were suggested as most important for the hydromorphological conditions of the site, resulted at 69.2% from hydropower use while for four other case study sites the declared most important pressures were suggested to be a consequence of, respectively, hazard prevention, land use change (reclamation of arable and pasture land along river reach, land use change in upstream river corridor (channelization for reclamation of arable and pasture land near river) and production of raw materials. The second most important pressures (Fig. 6 right) were again caused by hydropower (46.2%); however, hazard prevention (30.8%) and production of raw materials (15.4%) is responsible for a relatively large part of the hydromorphological issues at the case study sites as well.

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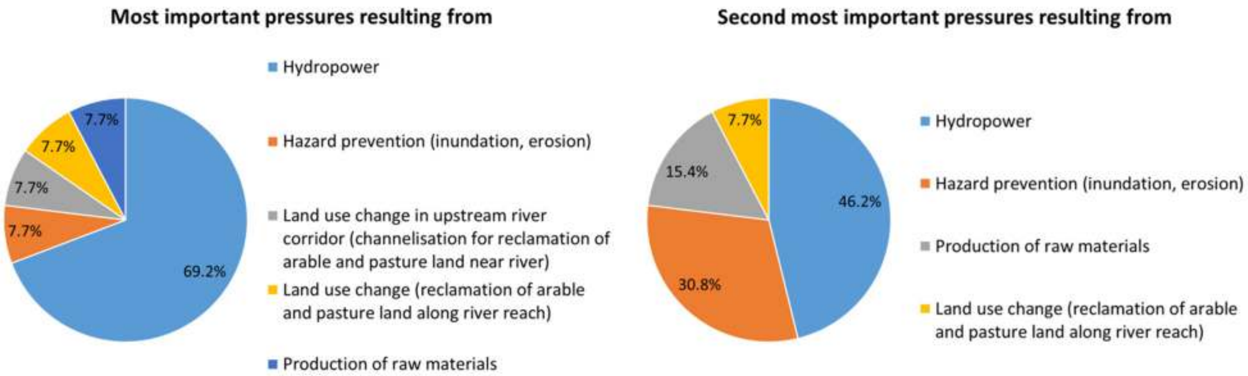

Fig. 6. Drivers that cause the most important pressures (left) and second most important pressures (right).

The relative distribution of all identified pressures is shown in Fig. 7. Among the 16 different recognised pressures sediment barriers (19.0%), river narrowing (14.3%) and water abstraction (9.5%) are mentioned most frequently.

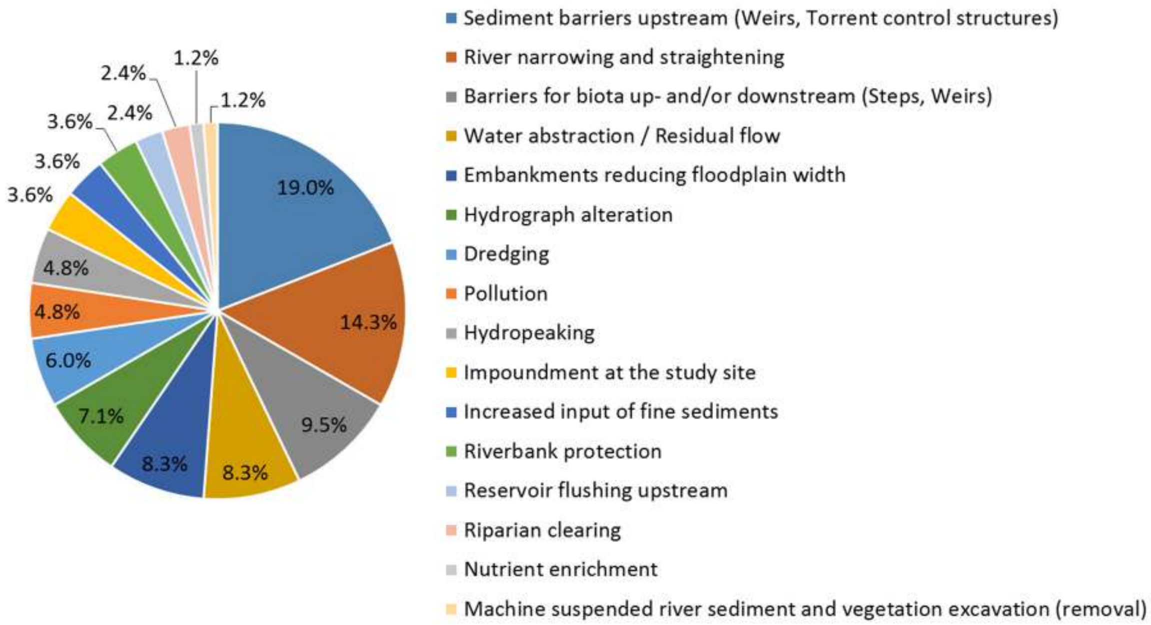

Fig. 7. Relative distribution of identified pressures at the HyMoCARES case study sites.

In Fig. 8 the 16 elaborated pressures are related to their occurrence at the 14 case study sites. It was found that all 14 case study sites are affected by sediment barriers upstream (dams, weirs, torrent control structures). Around 50% of the study sites are furthermore affected by river narrowing and straightening, barriers for biota, water abstraction, embankments and hydrograph alterations.

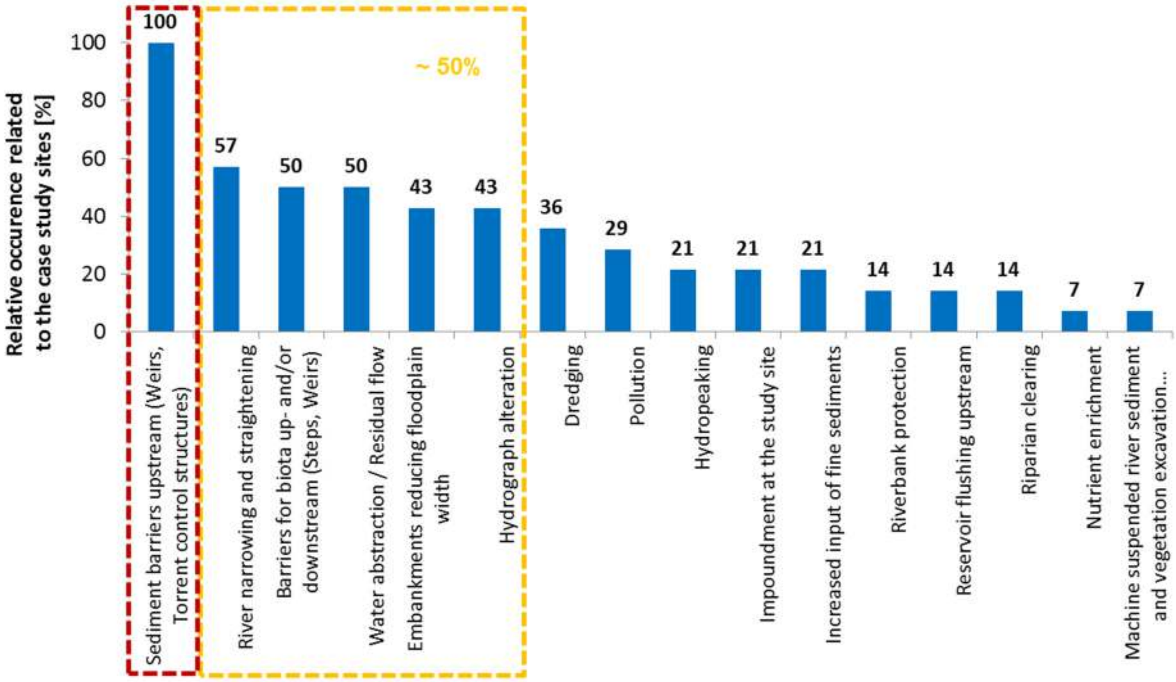

Fig. 8. Relative occurrence of all determined pressures at the HyMoCARES case study sites.

2.3.3. State

In the online survey a total sum of 440 states and 30 different types of states caused by the pressures in 0 were mentioned. The relative distribution of the identified states is shown in Fig. 9. The most often recognised hydromorphological states in this context are changes in sediment composition, increased flow velocities and a reduced lateral sediment transfer. In total the 10 most often mentioned states cover two thirds of the states.

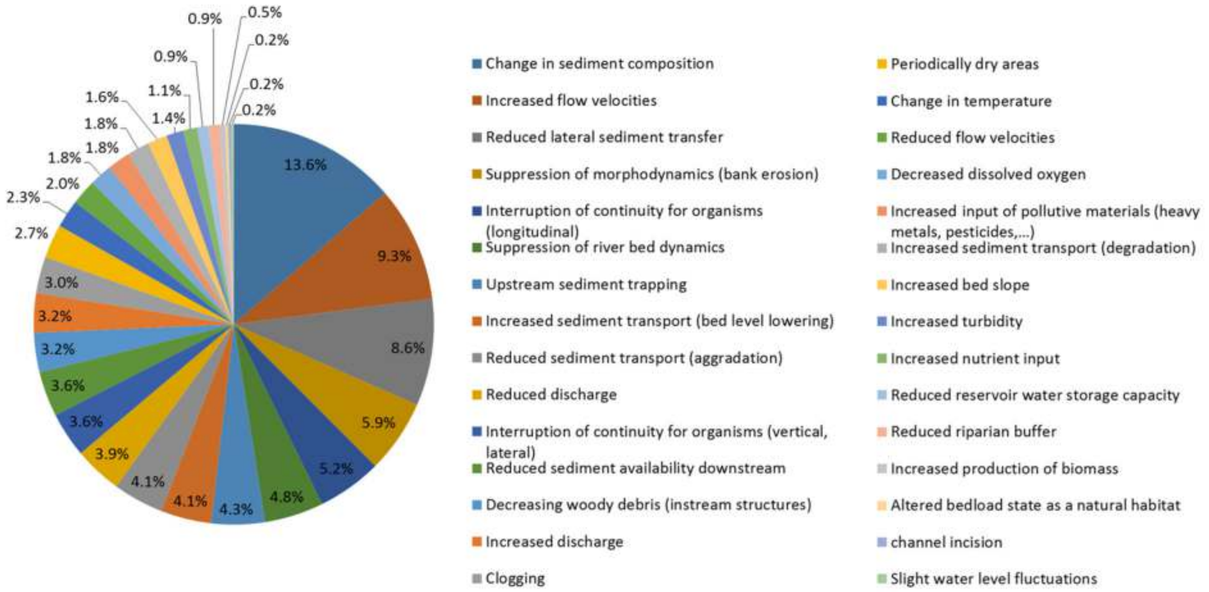

Fig. 9. Relative distribution of identified states among the HyMoCARES case study sites.

2.3.4. Impacts

In the online survey a total sum of 417 impacts and 14 different types of impacts caused by the states in 2.3.3 were mentioned. The relative distribution of the identified impacts is shown in Fig. 10. The 5 most often recognised hydromorphological impacts in this context are degradation of ecological status (17%), degradation of hydromorphological status (15.8%), negative impact on biodiversity (15.6%), loss of habitats (14.4%) and a negative impact on ground water level (12.0%). They cover 75% of all mentioned impacts in the HyMoCARES case study sites.

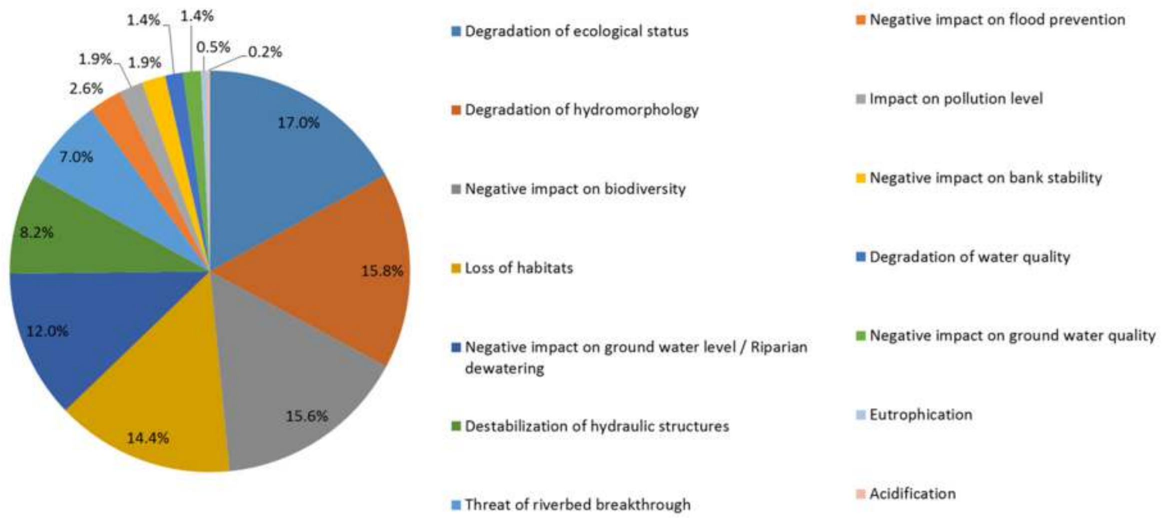

Fig. 10. Relative distribution of identified impacts among the HyMoCARES case study sites.

2.3.5. Responses

In the online survey a total sum of 263 responses and 14 different types of responses reacting to the impacts in 2.3.4 were mentioned. The relative deviation of the identified responses is shown in Fig. 11. The most often recognised hydromorphological responses among others in this context are restoration projects (15.2%), adaption of environmental policies (14.8 %), the establishment of a sediment management system for hydropower plants and torrent controls (11.4 %) and operation restrictions for hydropower plants (9.9%). Together these 4 measures cover over 50 % of all mentioned responses in the HyMoCARES case study sites.

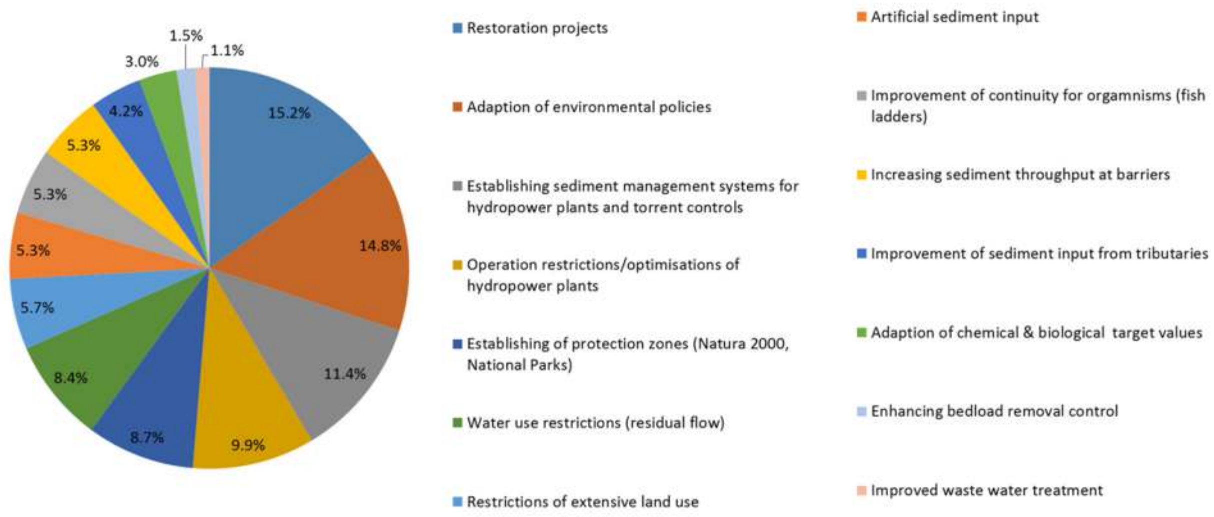

Fig. 11. Relative distribution of identified responses among the HyMoCARES case study sites.

3. Multi-scale concept for sediment-based restoration of Alpine rivers

The participants in the survey on hydromorphological issues at the HyMoCARES case study sites reported a major contribution of sediment barriers (e.g. hydropower plants, check dams) to the attested hydromorphological alteration. Sediment barriers affect downstream reaches, even if they are located far upstream. Next to anthropogenic pressures which act in situ at the reach scale, sediment barriers located upstream are of high significance as reported in the survey, confirming the urgent need of considering the catchment scale in the assessment of the hydromorphological condition. The aim here is to provide a framework for hydromorphological assessment, which finally supports the priorisation of counter measures as described in chapter 4.

The assessment procedure introduced here is based on the Hydromorphological Evaluation Tool (HYMET; Klösch and Habersack, 2018) with further developed indicators to improve as well as simplify the hydromorphological assessment. The consideration of several spatial scales is based on the River Scaling Concept (Habersack, 2000), the spatial delineation of river reaches may be conducted according to Gurnell et al. (2016). In contrast to HYMET, the assessment procedure developed here does not award scores, but ensures a consideration of all relevant river processes, providing a complete overview of the river's hydromorphological condition.

The designed assessment procedure includes two steps:

- Catchment evaluation: The step of catchment evaluation encompasses an assessment of sediment production, and an assessment of sediment retention behind barriers (quantity of sediment which is removed from the catchment-river system) and sediment removal.
- River reach evaluation: The evaluation in situ focuses on the artificiality of riverbed, riverbanks and river floodplain which affects the morphology given constraints defining the river course, river width or river bed levels. Additionally, the reach is screened for eventual disturbances through repeated sediment extraction of replenishment.

As a basis for understanding the relationships between catchment and reach-scale processes and the river hydromorphological state and trajectory of evolution, we introduce the conceptual basis in chapter 3.1.

3.1. Conceptual basis

In order to develop a multi-scale hydromorphological framework, the effects of catchment and reach-scale processes on a reach's hydromorphology need to be understood. Anthropogenic interventions affecting the largest scale of a river system, the catchment scale, determine the sediment supply into a river reach $Q_{s,in}$. At unchanged sediment supply conditions, interventions at reach scale of a river determine the deviations of the sediment transport out of the reach, $Q_{s,,out}$, from $Q_{s,in}$.

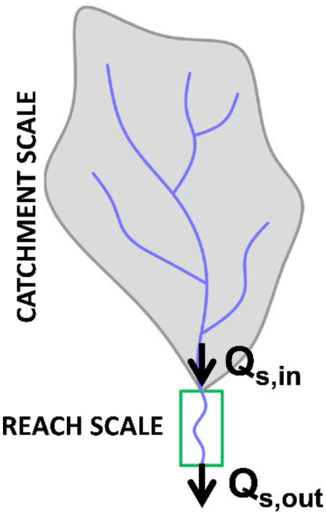

Fig. 12: Scales and sediment discharges considered in the sediment-based concept for river restoration.

Assuming that the supplied sediment is of similar texture as the eroded sediment and that both sediments exhibit a similar porosity, the relation between $Q_{s,in}$ and $Q_{s,,out}$ shows whether a reach would aggrade or degrade. In addition, the lateral morphodynamics of a river system are known to depend on the magnitude of sediment 'load' in the reach (Fig. 13).

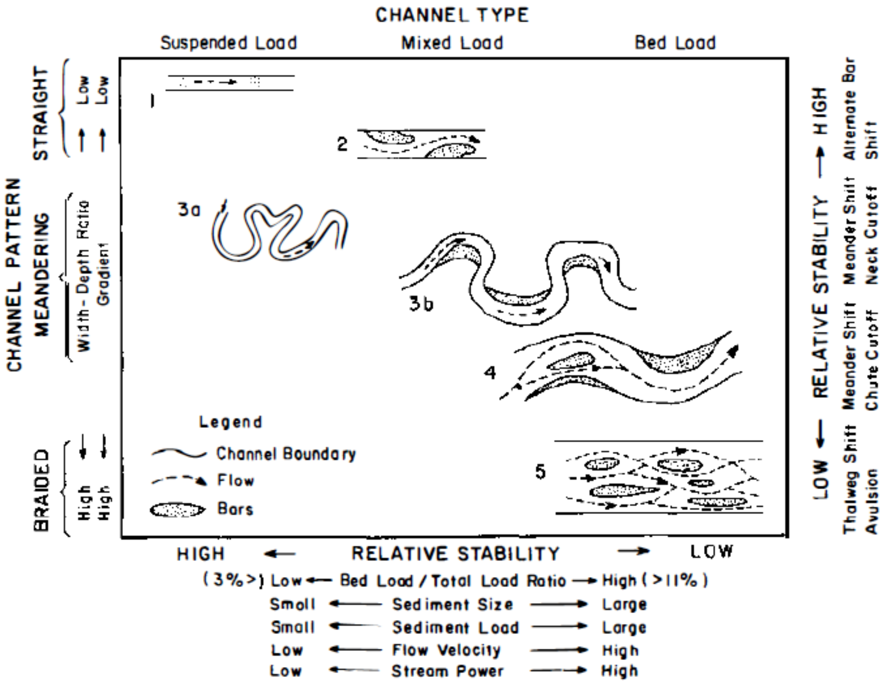

Fig. 13. Dependency of the river morphology on sediment characteristics, including sediment yield (Schumm, 1985).

A similar relationship was described by Church (2006), but for sediment 'supply' (Fig. 14). Note that natural rivers are in an equilibrium state of sediment budget, so that the sediment load in the reach is equivalent to the sediment supply.

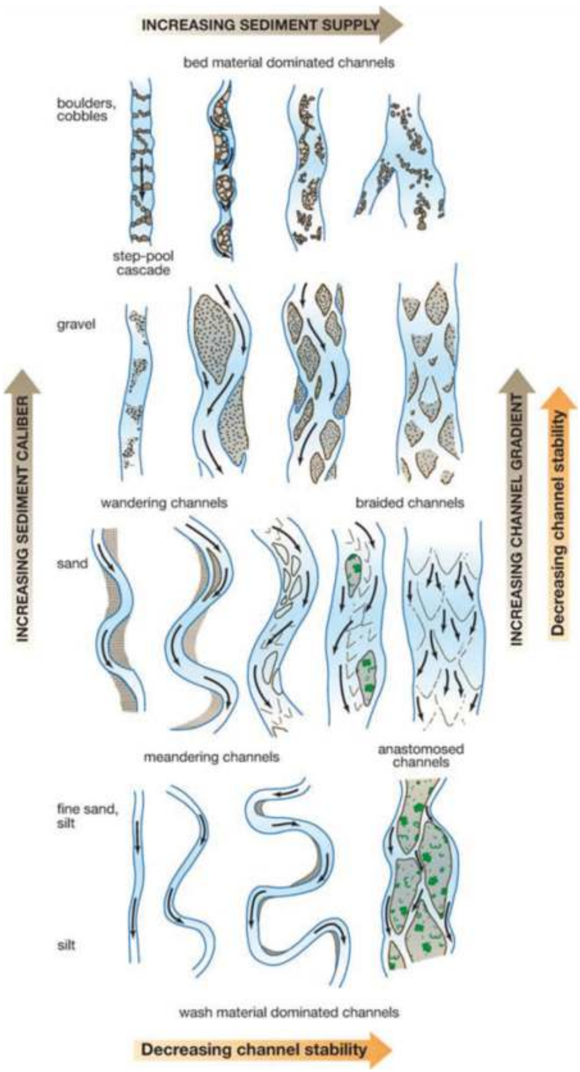

Fig. 14. Dependency of the river morphology on sediment characteristics, including sediment supply (Church, 2006).

More recently, Mueller and Pitlick (2014) found a good relation between the morphology and the bedload concentration, which is the bedload discharge in relation to the water discharge, hence supporting the relations found by Schumm (1985) and Church (2006).

Fig. 13 and Fig. 14 were derived from natural rivers with more or less stable conditions of the sediment budget, resulting in a constant sediment discharge in the considered river reach. In contrast, the sediment discharge in impacted river reaches varies within the reach during adjustment to external boundary conditions (changes in sediment supply or channelization) and depends on the magnitude of both, $Q_{s,in}$ and $Q_{s,out}$ (Fig. 15). As long as the sum $Q_{s,in}+Q_{s,out}$ remains unchanged, and assuming that bed level changes are uniformly distributed throughout the reach, the average sediment load is the same and amounts to $Q_s=(Q_{s,in}+Q_{s,out})/2$. Following this concept, the only difference at the common initial condition displayed in Fig. 15 is the distribution of the sediment load within the reach: In aggrading reaches the maximum sediment load is located towards the upstream end, in degrading reaches towards the downstream end of the reach.

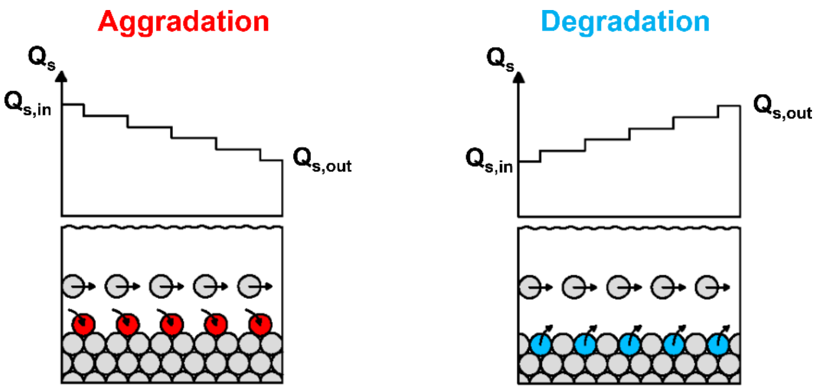

Fig. 15. Effects of uniform aggradation/degradation on the sediment discharge.

Over longer term, the bed aggradation will increase the slope of the river reach, until the sediment transport capacity corresponds to the increased $Q_{s,in}$, and the bed degradation will decrease the slope until the sediment transport capacity corresponds to decreased $Q_{s,in}$ (Fig. 16).

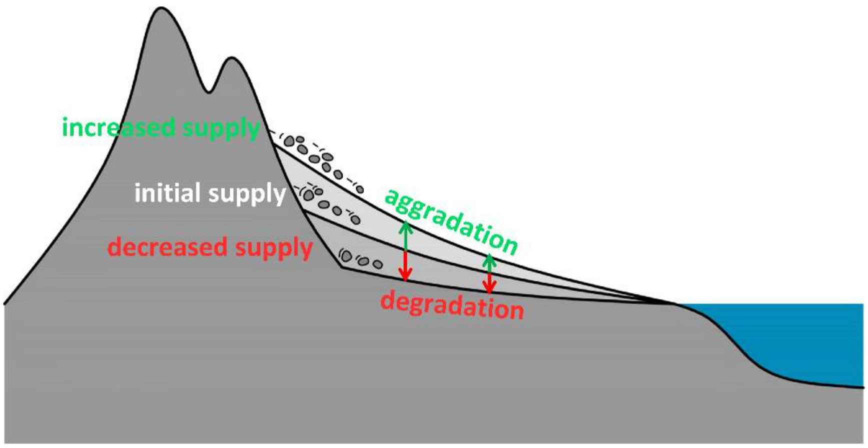

Fig. 16. Dependency of the channel slope on the sediment supply.

At unconstrained rivers, an increased sediment load leads to wider morphologies. Accordingly, in the concept for sediment-based river restoration, we describe the states 'wide' and 'narrow' relative to an initial state to be dependent on the sediment load. However, the riverbanks of the observed river reach may be protected, so that an increased bedload may not be able to result in lateral morphodynamics to obtain a wider morphology unless the bank protection structures are destabilised and/or eroded. Therefore, in the case of bank protections, we use the terms 'increased/ decreased lateral fluvial pressure' instead of 'wide' and 'narrow'.

3.2. The concept diagram

By relating $Q_{s,in}$ to $Q_{s,out}$, the following diagrams can be created (Fig. 17). In Fig. 17a, a 1:1 line separates the processes of aggradation and degradation. As the sediment budget may be subject to natural variations (e.g. due to infrequent sediment pulses from landslides in the catchment), the equilibrium is defined as a range instead of assigning it to the 1:1 line only. In Fig. 17b, the morphological type (narrow or wide) is assigned to the average sediment transport $Q_s=(Q_{s,in}+Q_{s,out})/2$, following Fig. 13 and Fig. 14. Note that the terms 'wide' and 'narrow' refer to the morphological type, not to the absolute width of the river.

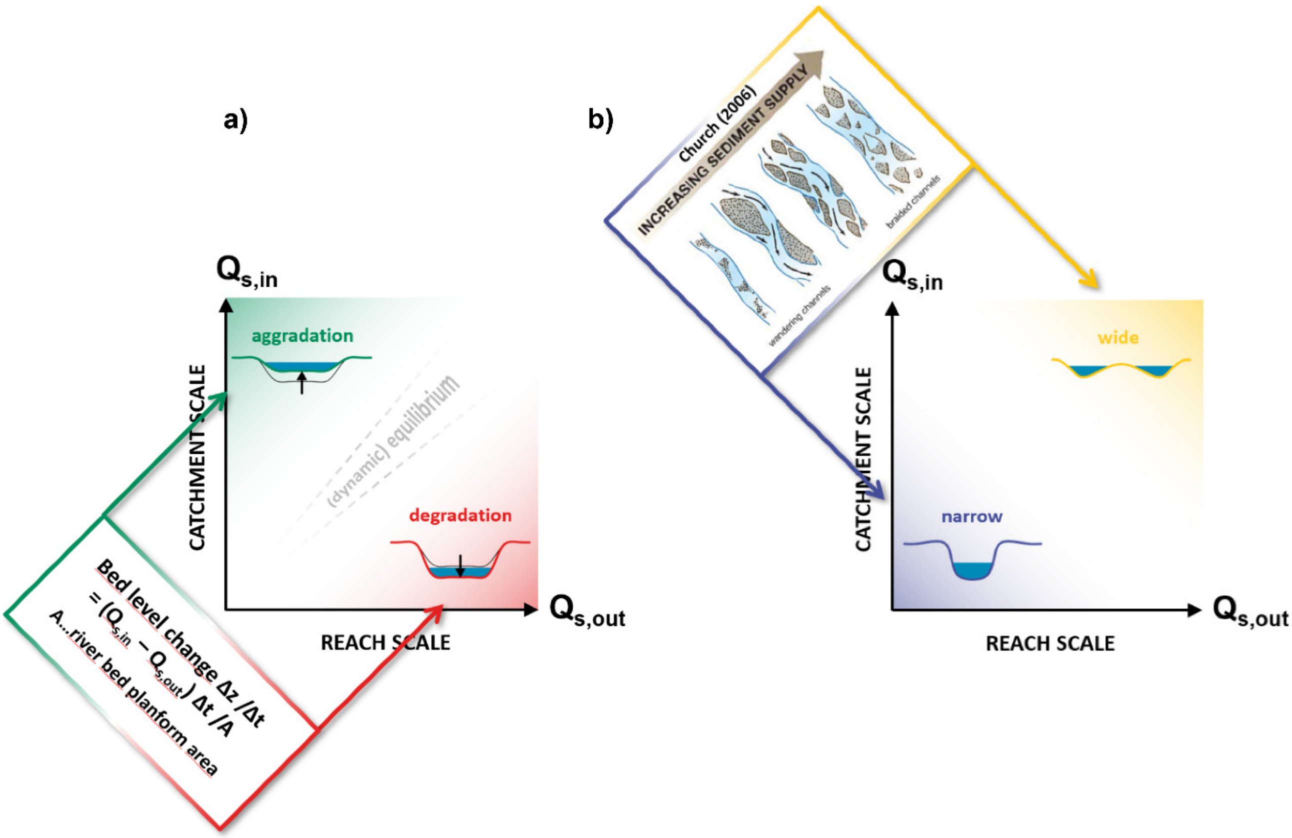

Fig. 17. a) Aggradation and degradation depending on the difference between $Q_{s,in}$ and $Q_{s,out}$, b) the width depending on the average sediment transport $Q_s=(Q_{s,in}+Q_{s,out})/2$.

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The diagram contents of Fig. 17a and Fig. 17b are merged in a single diagram (Fig. 18), which is the basis for the concept of sediment-based river restoration.

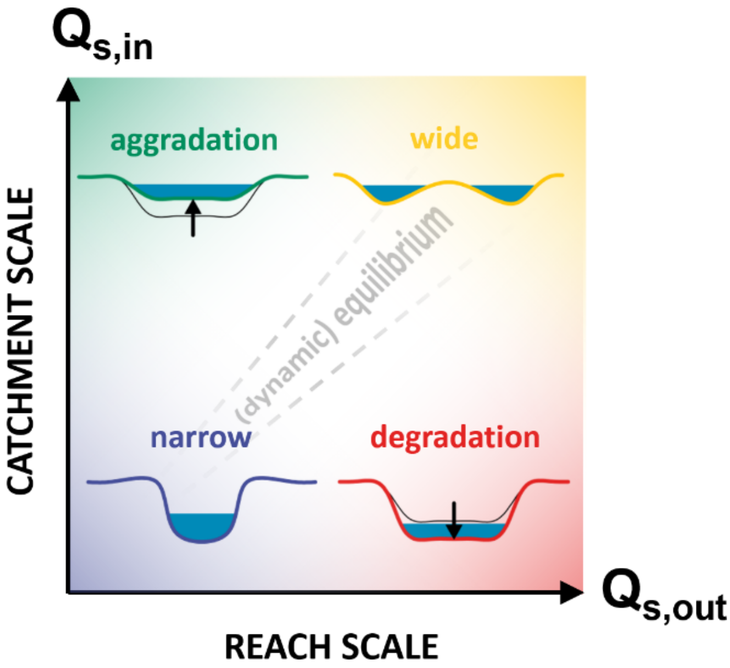


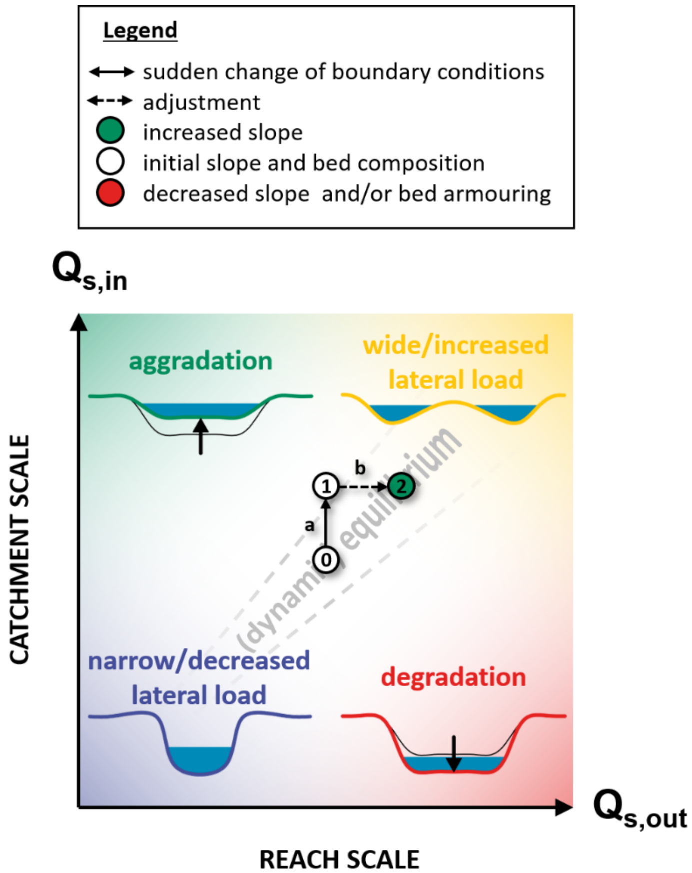
Fig. 18. Conceptual diagram for the sediment-based restoration of Alpine rivers.

It has to be considered that this established concept cannot account for all processes involved in the morphological development (e.g. effects from vegetation, specific structures).

3.3. Diagram application to estimate river trajectories

3.3.1. Increase of sediment supply

Re-establishment of sediment connectivity by e.g. dam removal, as well as artificial sediment replenishment are increasingly applied measures in river restoration. Starting from an initial condition in the diagram, Fig. 19 displays the trajectories that follow an increase of sediment supply.



Trajectory	Description
a	**Impact:** A sudden increase of the sediment supply into the reach shifts the reach into an aggrading state. First, the sediment discharge is increased especially in the upstream part, where the reach starts to develop a wider morphological type.
b	**Adjustment:** The sediment surplus increases the channel slope, until the reach is capable of transporting the increased sediment supply to the downstream end of the reach. At the end of adjustment, the reach obtains higher bed levels, a larger slope and a wider morphology throughout its entire length.

Fig. 19. The hydromorphological effects of an increase of sediment supply on the river reach.

A re-establishment of sediment connectivity will cause a permanent increase of sediment supply and a sustaining change of the morphology towards a wider morphological type. In contrast, the effect of sediment replenishment is temporary, if the replenishment action is a one-time measure or if replenishment actions occur within a limited period of time only.

The eruption of Mount St. Helens in 1980 serves as an illustrative example for an increase of sediment supply.

Volcanic activity caused a collapse of the top of the mountain, which mobilised 3 km^3 of sediment. Fig. 20 shows the widening effect and the slope increase of the North Fork Toutle River due to the increased sediment supply. As the increase of sediment supply was limited in time, trajectory b is overlapped by a simultaneous adjustment to a decrease of sediment supply after the initial peak. Sediment transport causes the sediment discharge to reduce again, and, over longer term, the river would evolve toward the state before eruption.

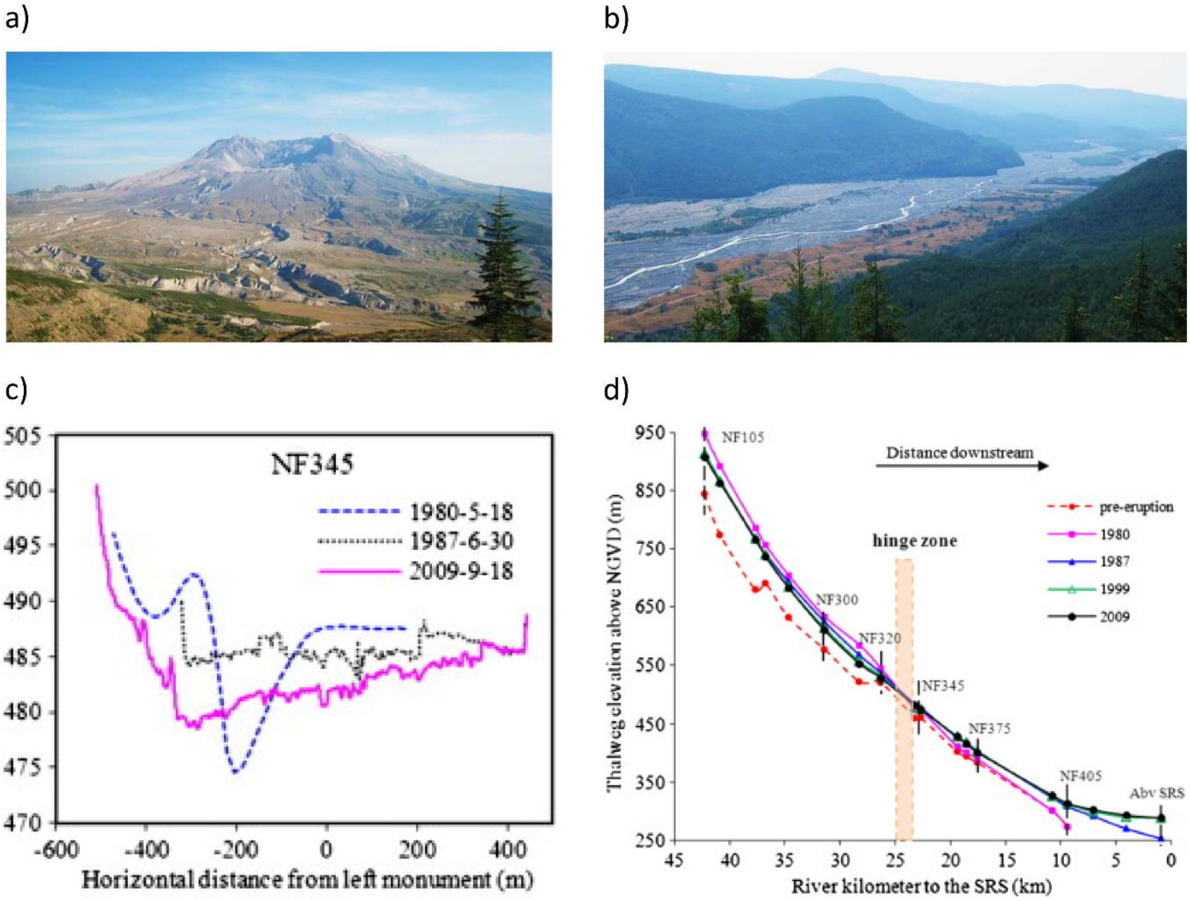
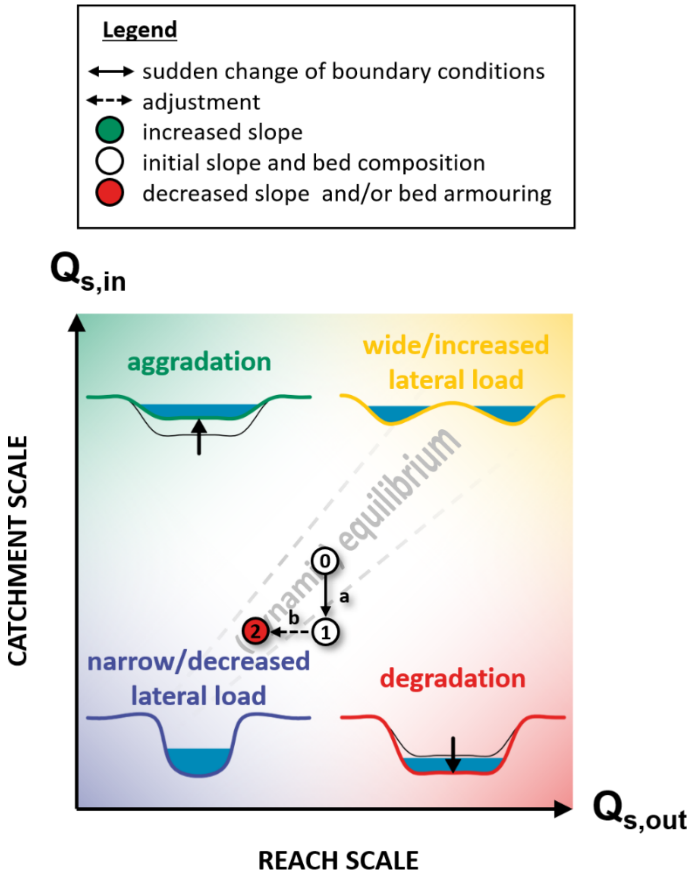


Fig. 20. The eruption of Mount St. Helens in 1980 caused an instantaneous increase of sediment supply: a) Mount St. Helens in 2009, b) wide morphology of the North Fork Toutle River in 2009, c) cross section with widened bed after eruption (Zheng et al., 2014), d) longitudinal profile with increased slope following the eruption (Zheng et al., 2014).

3.3.2. Decrease of sediment supply

Every kind of sediment retention in the catchment of a river reach (e.g. dam construction for hydropower, dredging, torrent control) causes a reduction of sediment supply into the reach. The hydromorphological consequences are displayed in Fig. 21.



Trajectory	Description
a	**Impact:** A sudden decrease of the sediment supply into the reach shifts the reach into an aggrading state. First, the sediment discharge is decreased especially in the upstream part, where the reach starts to develop a narrower morphological type.
b	**Adjustment:** Degradation decreases the channel slope, until the sediment transport capacity adjusted to the reduced sediment supply. The reach obtains lower bed levels, a smaller slope and a morphology of a narrower type throughout its entire length.

Fig. 21: The hydromorphological effects of a decrease of sediment supply on the river reach.

Marti and Bezzola (2009) showed in a laboratory experiment that, if the bedload supply was reduced to 20%, the river reach turned from a braided into a single-thread channel (Fig. 22), possessed an armoured bed and a decreased slope (from 2.12% to 1.92%). The reduction of the slope was limited as after some time degradation, which would have further decreased the slope, was prevented by the armouring of the river bed.

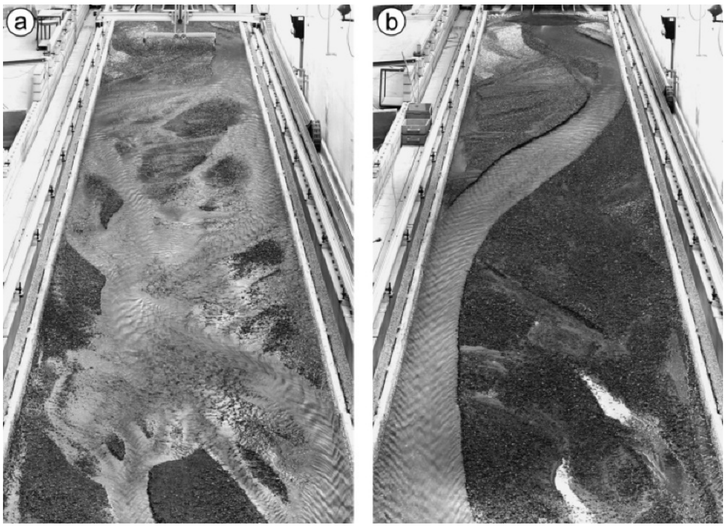
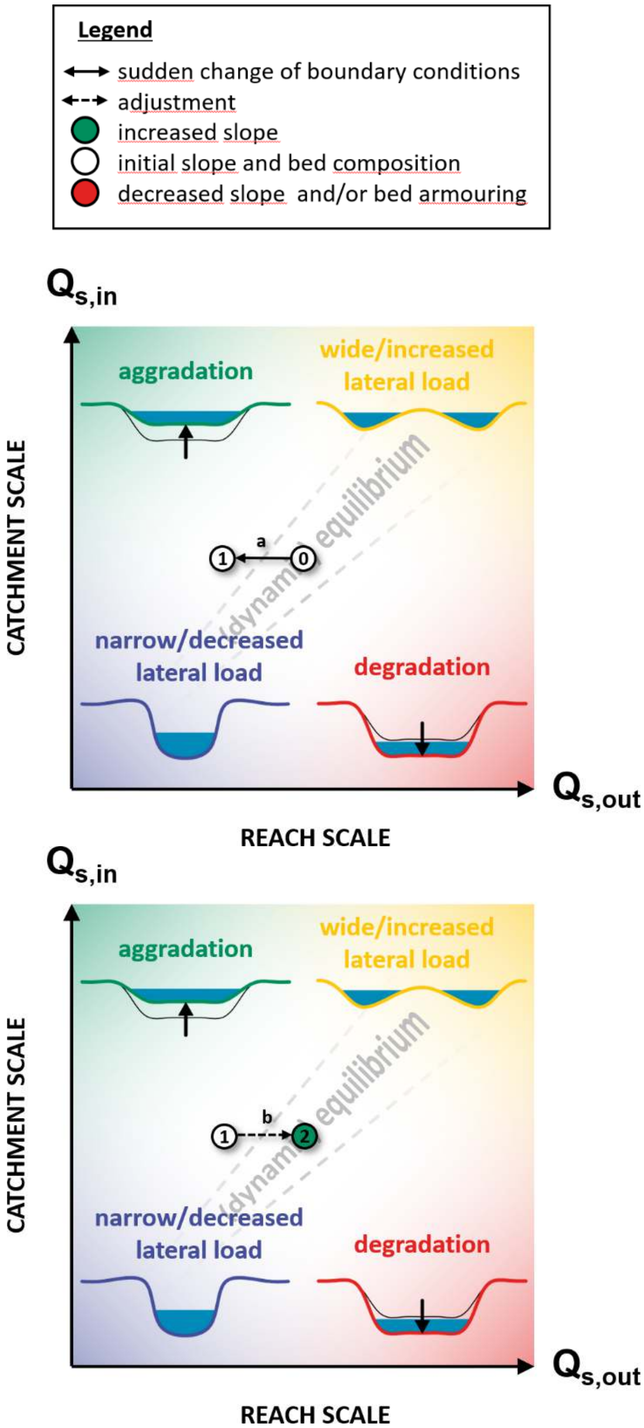


Fig. 22. Evolution from a braided to a single-thread channel after reduction of sediment supply (Marti and Bezzola, 2009).

3.3.3. Riverbed widening

Especially for Alpine rivers, which possessed wide morphologies in their alluvial floodplains, the river bed widening is the most appropriate measure in river restoration. Widenings may be constructed by excavators, or may be created by lateral erosion after solely removing the bank protections. If the banks contain grain sizes which are transported as bedload, the bank erosion temporarily increases the sediment supply. Fig. 23 displays the hydromorphological consequences of a constructed widening. In case of fluvially established widenings, the widening effect overlaps with a temporary increase of sediment supply.



Trajectory	Description
a	**Impact:** A sudden increase of channel width reduces the sediment transport capacity in the reach and the bed starts to aggrade. First, a more natural morphology appears in the upstream part, but due to aggradation the sediment discharge is reduced especially in downstream direction so that at the beginning, the morphology is of a more natural, but narrower type than the type corresponding to the undisturbed sediment discharge. The lateral load onto the banks is decreased in comparison to the narrowed state.
b	**Adjustment:** Due to the reduced sediment transport capacity in the widened reach the bed aggrades, until an increased slope is established, which allows the sediment to be transported through the entire reach. The reach obtains higher bed levels, a larger slope and a more natural morphology instead of a narrowed channel with increased lateral load.

Fig. 23. The hydromorphological effects of widening due to river restoration.

Fig. 24 shows a river section of the Drau River before and after widening. The bed widening was followed by the appearance of bars. The flow still occurs along protected banks. Accordingly, the load onto the banks may still be increased compared to the situation in a more natural state, unless the slope fully adjusted to these boundary conditions.

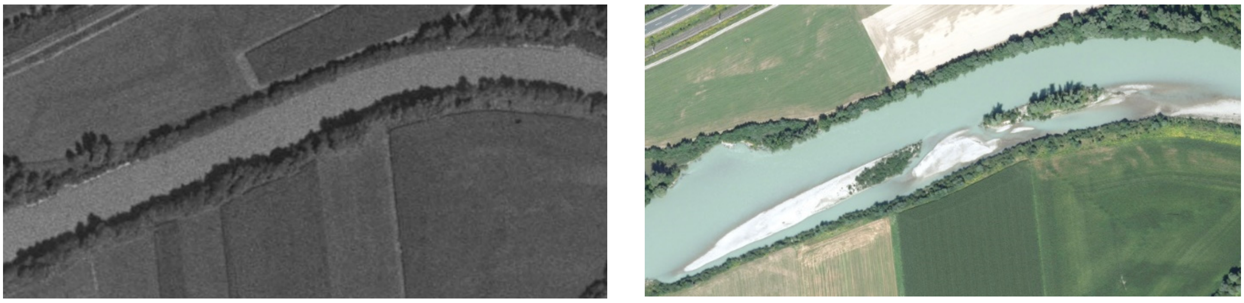
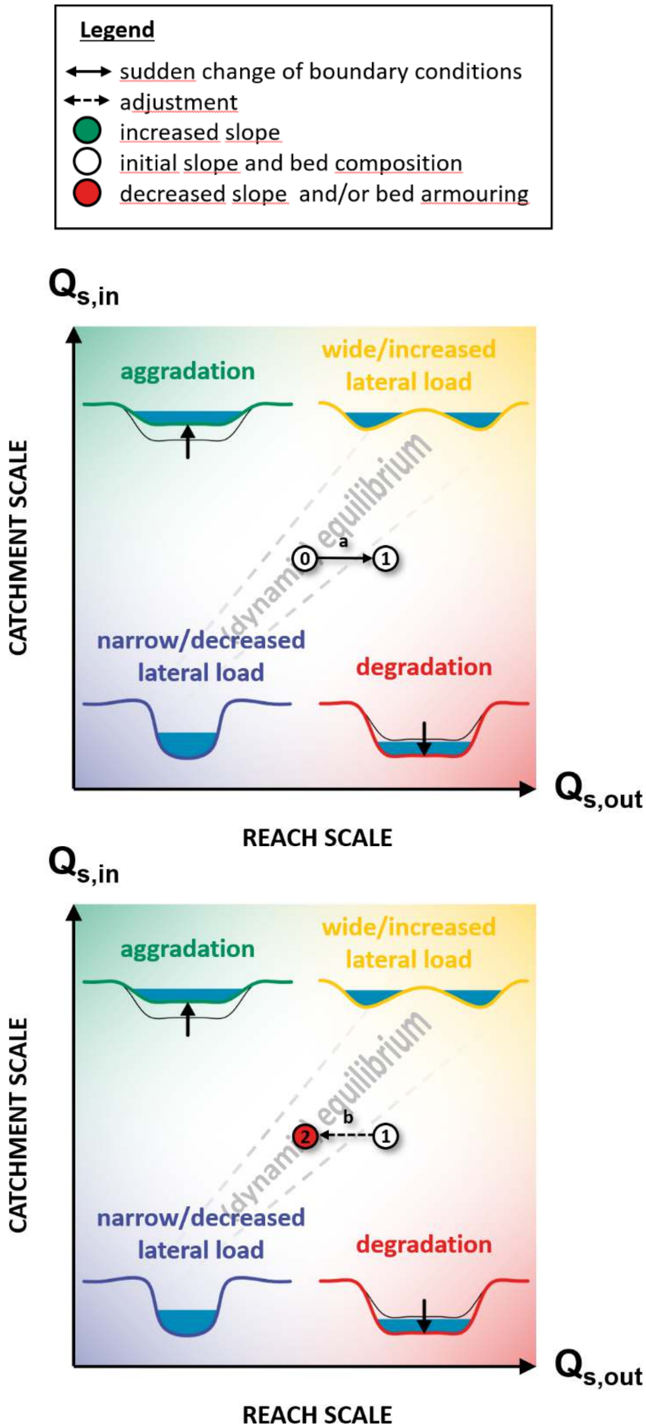


Fig. 24. Left: Section of the Drau River in the municipality of Kleblach-Lind in 1998 (left) and after bed widening in 2013 (right), source: Carinthian government.

3.3.4. River narrowing

Most of the Alpine rivers were affected by channelization, which included straightening of the river course and river narrowing. Fig. 25 depicts the effects of river narrowing.



Trajectory	Description
a	**Impact:** A sudden decrease of channel width increases the sediment transport capacity in the reach and the bed starts to degrade. The lateral load onto the banks is increased and the risk of destabilization of bank protection structures during larger events is increased.
b	**Adjustment:** The increased sediment transport capacity causes bed degradation, attempting to decrease the channel slope. Depending on the riverbed sediment characteristics, an armouring layer may develop which prevents further degradation, causing a temporary completion of trajectory b. The armouring layer may break up during larger events and further degradation with increased sediment transport may follow. If the degradation can fully adjust the slope to the narrowed condition, the lateral load is similar to the condition before narrowing also during larger events. However, the more natural morphology was replaced by a constrained channel.

Fig. 25. The hydromorphological effects of narrowing due to river channelization.

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In addition to narrowing, channelization works also included straightening of the river course, so that the slope of the channel (in state 1 in Fig. 25) would initially be increased. The slope may remain increased in comparison to the original state, if an armouring layer develops quickly. An increased slope combined with a narrowed channel may highly increase the risk of destabilized riverbanks, especially if the armouring layer breaks up during larger events and increases the sediment discharge.

An extreme flood at the Bregenzer Ach caused excessive widening after destabilisation of the bank protection structures, very likely due to the high sediment discharges during the event (Fig. 26).

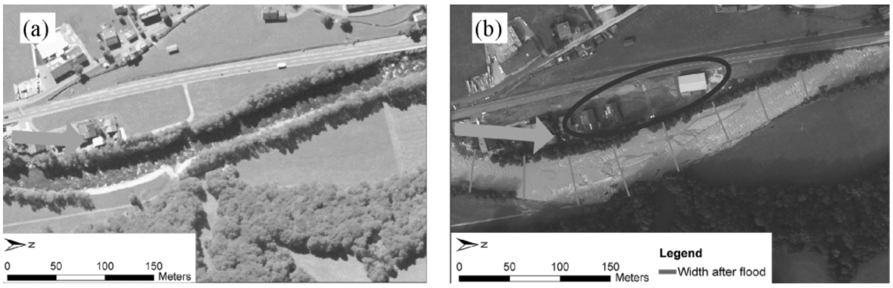

Fig. 26. Bregenzer Ach River before/after extreme flood (Krapesch et al. 2011)

The excessive widenings may be accompanied by severe destruction of bank protection structures (Fig. 27).

Fig. 27. Damages along Trisanna River after extreme flood (source: Baubezirksamt Imst).

3.3.5. Change of discharge

Changes of sediment supply are often combined with changes of discharge. Given flow regulation downstream of dams, the discharge frequency may be altered. Especially in the case of flow abstraction, the change of discharge is of high morphological relevance. The formula for the threshold bedload concentration between a single-thread and braiding morphology from Mueller and Pitlick (2014) helps to estimate the morphological consequences of water discharge changes.

3.4. Evaluation at catchment level

For a river reach downstream, the sediment supply entering the river reach co-determines the reach's hydromorphology. The catchment evaluation focuses on the sediment production in the catchment, the sediment retention behind eventual artificial sediment barriers and eventual artificial removal or supply of sediment. If there is no sediment barrier in the catchment upstream of the reach to be evaluated, the evaluator can directly start with the evaluation of sediment transfer. If the catchment of the reach to be evaluated is affected by sediment barriers, the first step in the catchment evaluation is to determine the relative productivity of affected sub-catchments in relation to the unaffected sub-catchments.
For the estimation of the relative sediment productivity, the following catchment properties are relevant:

- Geology
- Slopes in catchments
- Landcover
- Weathering

Based on these indicators, a relative productivity can be estimated for these sub-catchments. The Revised Universal Soil Loss Equation (RUSLE) is one example of using different data sets to calculate the sediment production by taking into account the rainfall erosivity, soil erodibility, slope characteristics, vegetation cover and land management practices (Fig. 28. Sediment production derived from the Revised Universal Soil Loss Equation model for the Alpine Space (JRC, European Commission, 2010).). However, the RUSLE is based on rainfall impact only, and does not account for mass wasting processes such as landslides and rock falls, as it was developed for cultivated land. Cavalli et al. (2013) calculated an index of connectivity using a digital elevation model of high resolution of a catchment to estimate the relative contribution of sub-catchments to sediment delivery to a defined catchment outlet (Fig. 29. Index of connectivity computed with reference to the outlet of the studied catchments (Cavalli et al., 2013).). However, again the sediment flow is only considered at the surface, without considering larger-scale sediment transfers such as landslides.

Another way to estimate catchment-scale sediment production is to map the active hillslope sediment sources which are connected to the stream network (e.g. landslides, debris flows, gullying areas…). Small-scale expert-based mapping approaches based on aerial photos as well as large-scale automatic detection methods based on remote sensing data are presented in a technical guideline of the Alpine Space SedAlp project (Brardinoni et al., 2015). This report is available online at the following link:

http://www.sedalp.eu/download/dwd/reports/WP4_Report_Annex.pdf

Such mapping procedures are of great interest since they really focus the investigation on the most critical geomorphic components of the catchment delivering sediment to the river. However, their implementation is not straightforward and necessitates advanced knowledge in geomorphic interpretation and mapping. Once sediment sources maps are available, it is easy to rank sub-catchments according to their potential of sediment delivery to the trunk channel.

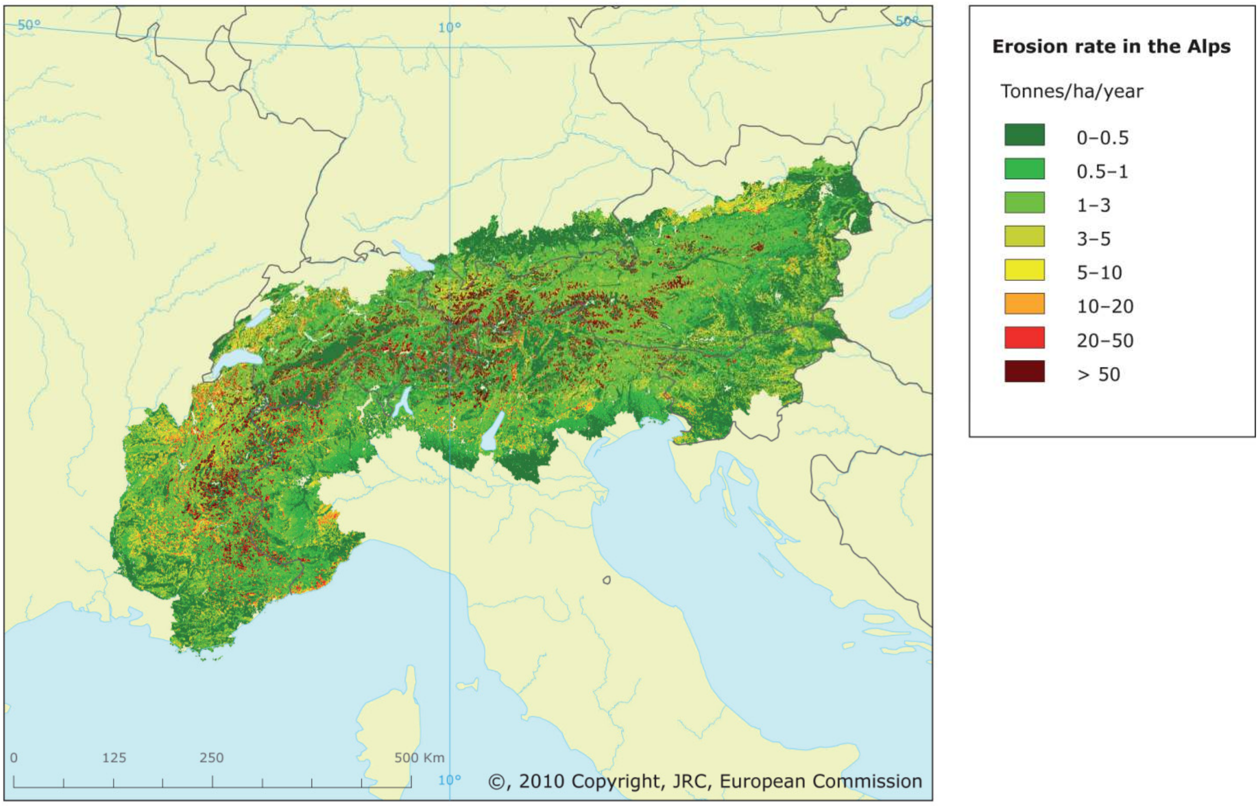

Fig. 28. Sediment production derived from the Revised Universal Soil Loss Equation model for the Alpine Space (JRC, European Commission, 2010).

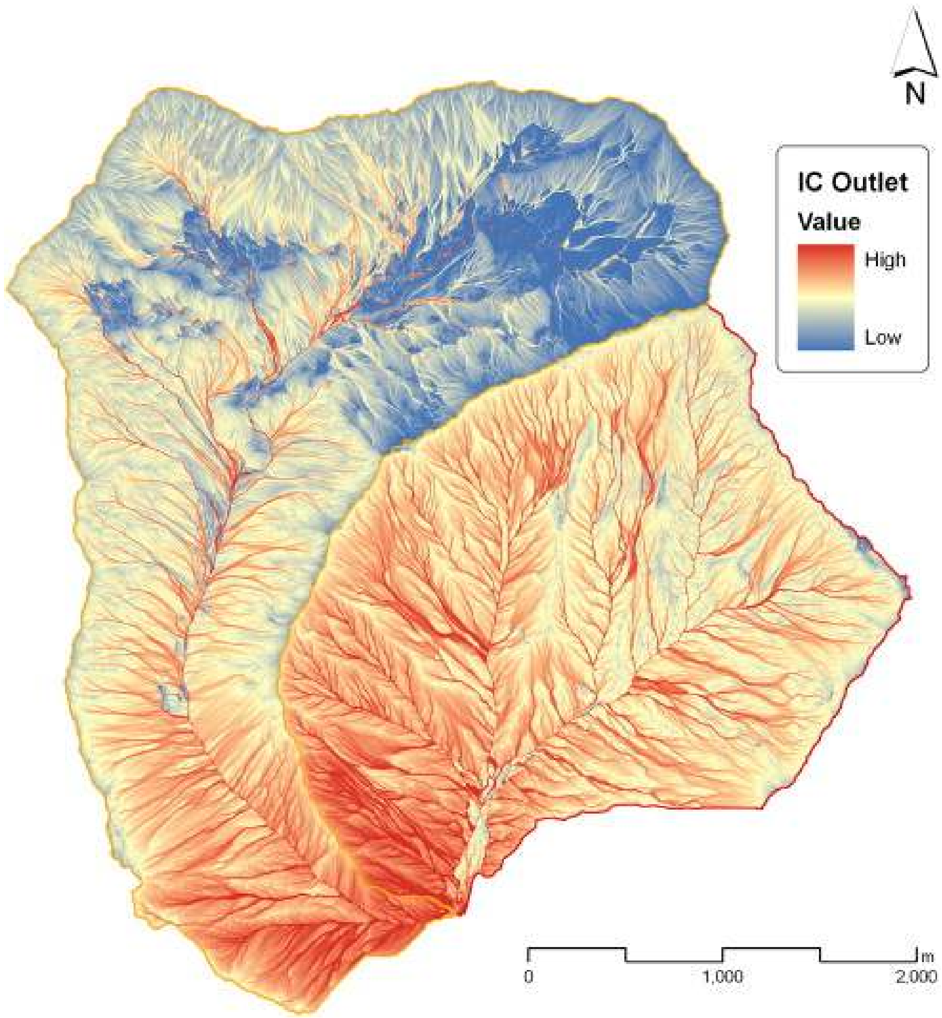

Fig. 29. Index of connectivity computed with reference to the outlet of the studied catchments (Cavalli et al., 2013).

In the second step of catchment evaluation, the sediment barriers located in the catchment are evaluated for their sediment permeability. For estimation of a barrier's permeability, the following characteristics are relevant:

- Sediment throughput - The sediment throughput needs to be evaluated over long time-scale, including e.g. flushing operation.
- Sediment extraction - Portion of sediment which is removed on total sediment which is supplied to a reservoir, e.g. dredging in reservoirs behind hydropower plants, check dams.
- Frequency of sediment release – The frequency of release of retained sediment determines the spatial extent of effects on the fluctuation of sediment supply.

- Quality change of sediment – Sediment retention is often size-selective: Fine sediment, which is transported as suspended load, is often transported with the flow through barriers, while coarser particles may deposit in upstream parts of reservoirs. At the same time, deposited fines are hard to remobilize given affects from cohesive forces between deposited particles and eventual biofilms increasing the critical shear stress of the sediment.

The following parameters of sediment barriers may be relevant for these characteristics:

- The elevation of the bottom of the weir (Sindelar et al., 2017)
- The width of the structure (Sindelar et al., 2017)
- The length of the reservoir
- The width/depth ratio in the reservoir
- available bypass systems
- The height of the structure during operation
- The volume of the reservoir
- The capacity of an eventual bottom outlet
- The shape of the reservoir bottom with respect to structures obstructing sediment transport
- The settling velocity (and hence settling time) of incoming suspended sediment
- water temperature (influences effectiveness of turbidity currents)

Considering the large variety of transversal structures, expert judgement may be applied for an evaluation of the above characteristics. Finally, the sediment permeability of a sediment barrier may be represented by a throughput coefficient as performed by Klösch and Habersack (2018)(Fig. 30). Malavoi et al. (2015) propose to assess the impact of a sediment barrier by comparing the sedimentary states of the river reach downstream with a reference reach upstream of the sediment barrier.

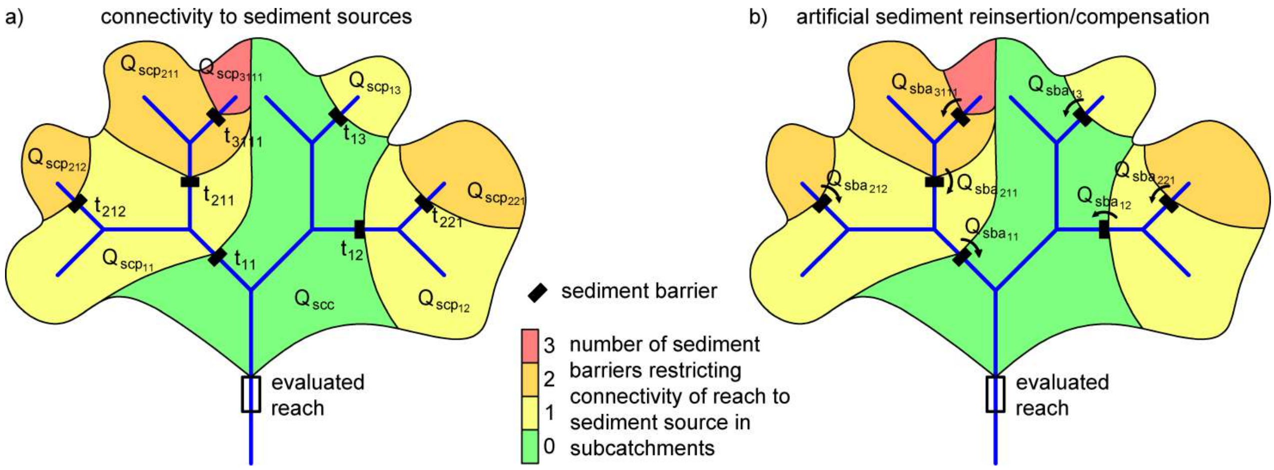

Fig. 30. Throughput coefficients t_{ijkl} assigned to sediment barriers, as well as sediment replenishment activities (Q_{sba}) considered in the Hydromorphological Evaluation Tool to assess the sediment discharge entering the evaluated reach relative to the sediment production (Klösch and Habersack, 2017).

The sediment connectivity of a river reach to its catchment then needs to be represented by a catchment factor F_C between 0 and 1. F_C can then be translated into a catchment score by applying the exponent a, which adjusts the marking thresholds as depicted in Table 1. It is to be found out during testing and intercalibration whether the exponent *a* needs to be varied depending on the type of the Alpine river. The catchment factor F_C and the exponent s are later used to determine a final, multi-scale score for the reach's hydromorphological condition in chapter 3.6.

Table 1. Marking at the catchment level based on the catchment factor F_C.

$(F_C)^a$	Score at catchment level (Sc)	Connectivity of reach to sediment production in its catchment
0.0 - 0.2	5	very bad
0.2 - 0.4	4	bad
0.4 - 0.6	3	acceptable
0.6 - 0.8	2	good
0.8 - 1.0	1	very good

If the score at the catchment level is below an acceptable situation (S_C=4 or 5), and the purpose is of the analysis is just to see whether the total hydromorphological situation is acceptable, the evaluation may stop here as this score is the maximum possible multiscale score after reach-scale evaluation, given the multiplicative method.

3.5. Evaluation at river reach level

3.5.1. The river freedom index RFI – assessment of channel constraints at reach-scale

At the scale of the reach level, the deviation of the hydromorphology from an undisturbed state is determined by artificial constraints which are imposed by human activities such as river regulation. These constraints may act laterally or vertically. The spatial extent of a river reach as the unit for the hydromorphological assessment may be delineated by the method of Gurnell et al. (2016).

A river reach may be constrained laterally by:

- Bank protections (e.g. riprap, walls)
- Groynes

and vertically by:

- Sills
- Bed pavement

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- Any transversal structure in the reach acting as an erosion basis

The lateral river freedom index RFI_l

As an indicator of the lateral boundary conditions for the hydromorphological state at the reach level, we suggest an analysis of the artificiality along the water edge of selected discharges, supposing that the frequency of direct contact between constraints and the flow reflects the reach's artificiality with respect to regulation. The selection of the discharge plays a crucial role in analysing the artificiality along the water edges. Smaller discharges may be carried in a narrow channel at a distance to the channel constraints, while the water edges of larger discharges in the same reach may be constrained by the bank protections. To reflect a full picture of the artificiality, we suggest analysing the water edges of a range of discharges.

In the field, it is challenging to estimate the locations of water edges for several discharges. To ease the application, instead of defining discharges, the following four water edge locations are represented as follows:

- **1st water edge:** The surveys should be conducted in periods of low flow, which in Alpine Rivers is during winter, usually January and February), The selection of the low flow period ensures comparability and replicability of the assessment. The artificiality is assessed along the observed water edge of that low flow discharge. Note that during that survey also submerged constraints need to be considered. Usually, at the clear water during low flow condition, all structures constraining the flow laterally are visible even if they are submerged.
- **2nd water edge:** The threshold elevation between bare sediment and the growth of vegetation represents the water edge of some higher discharge around mean flow. Vegetated bars (i.e. elevated morphologic features below floodplain elevation) with a longitudinal dimension smaller than half the width between the outer water edges (i.e. vegetation thresholds) are not considered. Every constraint which is present between the low flow water edge and this line needs to be recorded. Constraints already recorded at the analysis of the low flow water edge (e.g. groins fully submerged at low flow) must not be considered here a second time, unless they reach or exceed the elevation of the line of vegetation.
- **3rd water edge:** The bank edges (top of the banks) reflect the water edges of bankfull discharge. Only constraints partly or fully located between the 2nd and this water edge (i.e. bank edge) should be considered. The bank edges of Islands (i.e. morphologic features at similar elevation as the floodplain) with a longitudinal dimension smaller than that resolution are neglected.
- **4th water edge:** The length of levees or other constraining structures located in the inundation area of a 100-year flood measured along the channel centre line reflects the artificiality of the water edges flood flow.

Fig. 31 shows exemplified water edges (the 1st, 2nd, and 3rd) for a natural and an artificial situation.

a) b)

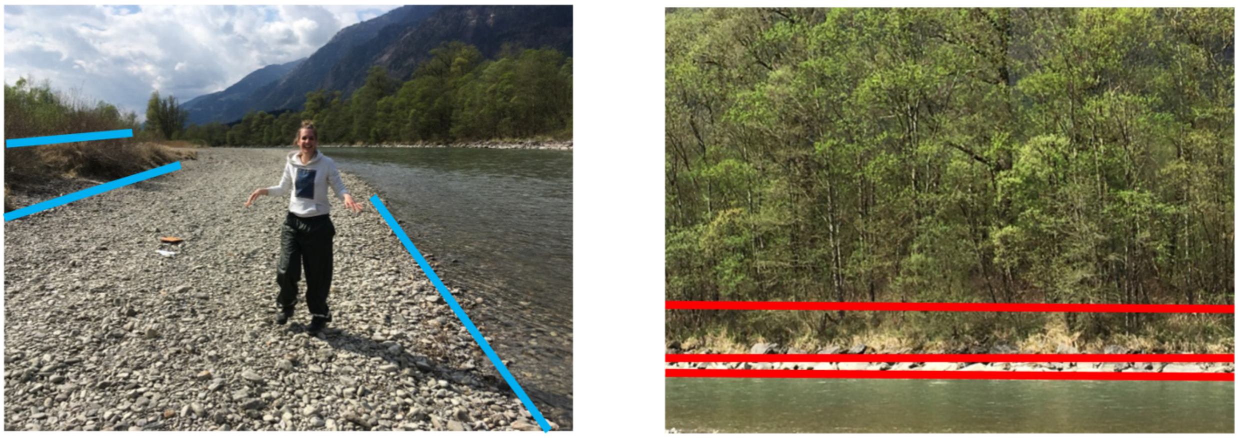


Fig. 31. Water edge of low flow, the threshold line of vegetation, and the bank edges for a) a natural bank, b) a bank artificially protected from erosive flow by riprap.

The survey should be conducted in the field during low flow condition, covering the first of the above-mentioned water edge analysis. The 2nd and 3rd water edge locations are analysed during the same field visit; while for the length of constraining structures in the floodplain the use of orthophotos and a related analysis using a Geographic Information System is more effective given the wide areas to be analysed. The potential contact of levees with the flow is self-explanatory, while other objects (e.g. infrastructure such as roads or railways) need to be analysed for their potential contact with the flow by using flood maps (such as the flood hazard maps required by the EU floods directive).

The position of the water edge needs to be surveyed at:

- Every local artificial constraint (e.g. groyne)
- Every change between artificial and natural water edge (e.g. change from bank protected with riprap and natural bank, or between constraining, but natural rock and artificial bank protection, and vice versa)
- a resolution half the width of the water surface, which spans between the analysed water edges. This resolution needs to be maintained to represent the course of the river geometry at sufficient accuracy.

Fig. 32 suggest a notation for the survey in the field.

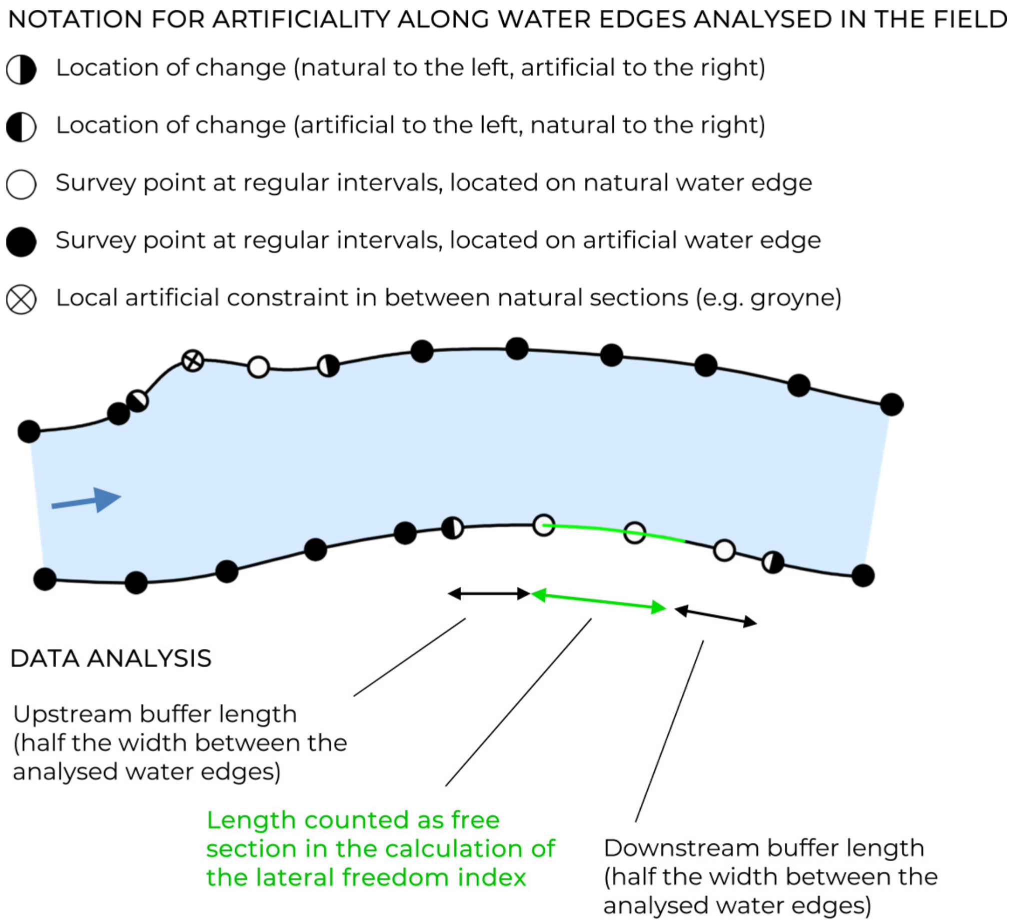


Fig. 32. Suggested notation for artificiality along one of the water edges to be analysed. Each point needs a record of its location (e.g. GPS).

The survey may be conducted in the field by using a GIS, or by using orthophotos in a GIS system complemented by the knowledge of site specifics of the user. At each surveyed point, the type of information is recorded:

- local, artificial constraint, or,
- change between natural (unconstrained or naturally constrained) and artificial condition (and vice versa).

To accelerate the survey, the user may consider already in the field that the length of an unconstrained water edge needs to exceed the width between the left and right water edge to count as an unconstrained bank section in the final evaluation.

The partial lateral freedom indices (for each of the four analysed water edges) are then calculated via:

$$f_{li} = \frac{L_{ni}}{L_i}$$

Where L_{ni} is the natural length of water edge i (with buffer sections subtracted as depicted in Fig. 32). The final **lateral freedom index f_l** is based on the sum of the partial indices divided by 4, so that the maximum possible value is 1:
:

$$RFI_l = \frac{f_{l1} + f_{l2} + f_{l3} + f_{l4}}{4}$$

The vertical river freedom index RFI_v

Vertical constraints (transversal structures such as. sills, ramps, weirs, or extensive bed protection such as pavement) are installed to maintain the riverbed at a certain elevation, most often indicating problems of bed degradation before implementation. Transveral structures often serve as parts of hydropower plants (e.g. diversion structure), then affecting the up- and downstream morphology due to the retention effects on water and sediment. Given the strong effect of vertical constraints the **vertical river freedom index RFI_v** is set to zero for the analysed reach if it contains any vertical constraint. However, the structure(s) may become inactive when they are covered by sediment due to aggradation, so that they can be neglected in the analysis.

The river freedom index (RFI) of the evaluated reach is then calculated via:

$$RFI = RFI_l \cdot RFI_v$$

where the maximum value for the RFI is 1.

3.5.2. Indicator for artificial dredging and replenishment activities

For reaches which are repeatedly replenished with sediment as part of a contract (e.g. sediment compensation downstream of a dam) or where sediment is repeatedly extracted (e.g. repeated aggradation increasing flood risk), occurring directly in the considered reach, the **index of sediment disturbance f_d** is set to 0. If not affected by these interventions, this evaluation does not affect the river reaches downstream of the excavation or replenishment sites, as there the change in sediment supply is already considered at the evaluation at the catchment level.

f_d is set back to 1, if

- the frequency of the disturbing activity is less than 1 yr^{-1}, and,
- The disturbing activity was followed by a flow event which exceeded the discharge of an annual flood.

3.5.3. Calculation of the reach-scale factor

the hydromorphological reach-scale factor F_R is calculated via:

$$F_R = RFI \cdot f_d$$

Note that there is no reach-scale score which is based on F_R only. The multiscale-factor, which is calculated in chapter 3.6 corresponds to a score at reach level, because at reach level both – catchment and reach scale – need to be considered.

3.6. Calculation of the multi-scale score

Based on the catchment factor F_C and the reach-scale factor F_R the multi-scale score is calculated, which - through intercalibration – may be adjusted to correspond to a shared perception of ecological status based on the monitoring of biota. The adjustment may be achieved via exponents, separately for the F_C and F_R, so that the final, multi-scale score S of the hydromorphological condition is calculated via:

$$S = {F_C}^a {F_R}^b$$

where *b* is a further exponent. The values of the exponents need to be found during the test application phase in the project through intercalibration with biological assessments. It is further to be found out whether the exponents need to be varied given different relevance of the considered hydromorphological boundary conditions.

Table 2. Marking thresholds to derive the multiscale score S at the reach level based on the catchment factor FC and the reach factor FR.

$(F_C)^a$ x $(F_R)^b$	Multi-scale score S	Preconditions for sustainable morphodynamics in reach
0.0 - 0.2	5	very bad
0.2 - 0.4	4	bad
0.4 - 0.6	3	acceptable
0.6 - 0.8	2	good
0.8 - 1.0	1	very good

Finally, it has to be noted that the obtained multi-scale score evaluates rather the hydromorphological boundary conditions than the actual hydromorphological state itself. This has to be considered when river reaches are adjusting to recent changes (e.g. recovering from intense gravel mining at the site), where the multiscale score is to be seen more like the state the reach is developing to as sediment transport continues.

4. Measure priorisation

For an economic and effective use of the resources available for river restoration, a priorisation needs to be conducted. We suggest a priorisation based on the following steps:

1. the observation of channel changes in river reaches
2. the identification of the risks which are related to these changes
3. Selection of the most demanding reaches based on the combination of risk and change
4. the identification of the causes for these changes in the selected reaches based on the hydromorphological assessment procedure
5. Identification of the most effective restoration measure (e.g. removal of sediment barriers re-establishing most sediment supply), considering also the time lag until measures become effective for the target reaches (e.g. using the HyMoCARES tool SedRace for an estimation of the sediment transfer velocity)

This list of the most demanding measures needs to be updated frequently based on continued observation.

4.1. Assessment of channel changes

An evaluation of the river network delivers information on the boundary conditions for the evaluated reach regarding sediment supply, and hence determines the sustainability of a reach's morphology as sediment supply co-determines the morphologic condition. For that purpose, the river network is analysed for an eventual state of disequilibrium.
The river network's condition may be assessed directly via an assessment of the sediment budget along the river network itself, or estimated from an indirect analysis via the assessment of a reach's trajectory.
Alternatively, if the relevant data is missing, the trajectory of a reach may be estimated at reach level as a proxy for assessing the state of sediment transfer. Then, however, the result is superimposed by local adjustments if boundary conditions at the reach level were changed (e.g. adjustment to removed bank protection structures). The following tools may be used for the assessment of a reach's trajectory:

- HyMoCARES Chevo, as introduced as a new tool below
- The Bed Relief Index (Liébault et al., 2013).
- The Bed elevation frequency distribution (Redolfi et al., 2016)

4.1.1. HyMoCARES Chevo – Tool for standardized assessment of channel evolution

Problem definition

River engineering measures are often preceded and followed by monitoring programs, serving for preservation of evidence and to assess whether or when eventual changes require corrective countermeasures or maintenance. One method to assess the evolution of the channel geometry is the repeated survey of river cross sections. The surveys are then often used for an assessment of morphologic characteristics, including the implications for the habitats of riverine species. Most often, the focus is on the assessment of degradation and aggradation tendencies as these affect the sustainability of an actual state from technical and ecological point of view. One problem, which is always encountered during the analysis of surveyed data, is a lack of a standardized method for such analyses.

In the analysis of a river's morphologic state, the characteristics of the flow, especially the water level elevation, the number of channels in the case of braiding, the lateral position of the channel(s) and the channel width, are of highest interest. For the flow of water, there is a difference if the channel changes occur laterally (e.g. bank erosion), or if they occur vertically (e.g. degradation of the bed) as these changes have different effects on hydraulic characteristics of the channel boundary (e.g. the hydraulic radius R, which is calculated by $R = A/U$, with A = cross-sectional area of the flow, and U = wetted perimeter of the cross section). Consequently, a sediment budget analyses (by equally considering all channel changes detected in a cross section) does not reflect the conditions for the flow. However, it is the flow and the related characteristics, which determine the appearance of a river and its interactions with the surrounding environment. A corresponding method, which determines the channel state and the channel changes under consideration of the flow characteristics, is still missing.

Aim

The aim of the proposed tool is to provide a standardized methodology for the assessment of channel changes, and to provide an easily available and applicable tool for its application.

The list of assessed channel characteristics should contain:

- Mean bed elevation
- Elevation of Thalweg (deepest) point
- Water surface elevation
- Width of water surface
- Number of channels in a cross section
- Mean water depth
- Average flow velocity

The following channel changes between two states of a cross section should be assessed:

- Bed aggradation/degradation (calculated from mean bed elevations)
- Change of thalweg elevation

- Bank accretion/erosion
- Channel widening/narrowing
- Channel migration
- Changes between single-thread and braiding state

One further aim is to relate these morphodynamics to the hydrologic conditions between the two surveys. Consideration of the flow events between the surveys should allow comparing the susceptibility to channel changes for different time intervals.
The final aim is to provide methods of visualization, which display the most relevant channel changes for eased and quick data analysis by the target users. In presentations prepared by the project partners and target users, the provided visualisations should illustrate the relationships between lateral and vertical channel changes, as well as display the channel changes followed by interventions in a comprehensible manner.

Methods and Application

<u>Selection of a reference discharge</u>
The assessment of channel changes requires the definition of the river channel from the provided cross section data, which usually contain also parts of an eventual floodplain or hillslopes. To allow automated analyses and to avoid subjectivity in the selection of the channel's lateral extent, we suggest restricting the analysed portion to the wetted part of a defined discharge. In river restoration, the effective discharge Q_{eff} is recommended for design purposes of the restored channel. Q_{eff} is the discharge which transports the largest sediment load over a period of years (Andrews 1980). Accordingly, a dominant role was assigned to this discharge in forming a river's morphology, and the effective discharge is now proposed here to delineate the wetted perimeter which is used for analysis of the channel changes.

The calculation of Q_{eff} requires a sediment rating curve, and a discharge frequency distribution which was derived from a time period which should at least cover 10 to 15 years (Shields et al., 2008). The bedload tool (described in this deliverable) can be used to assess the effective discharge by applying the derived sediment rating curve. The increments of discharge frequency distribution need to be multiplied with the corresponding sediment transport rate using the sediment rating curve. The discharge increment yielding the largest product then delivers the value for Q_{eff} (Fig. 33).

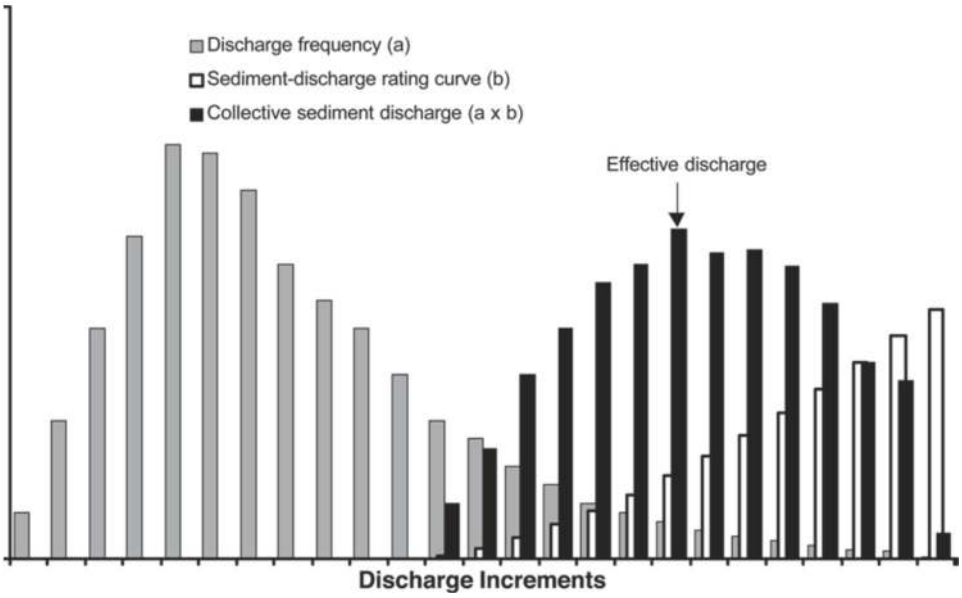


Fig. 33. Determination of the effective discharge from the discharge frequency and the sediment rating curve. Multiplication yields the discharge which transports most of the sediment (Shields et al., 2008).

If data is lacking for the calculation of Q_{eff}, or if uncertainties in sediment sampling and the selection of an appropriate sediment formula are assumed to be too large, one alternative is to use the discharge of a one-year flood as these values were reported to be quite similar (e.g. Crowder and Knapp, 2005) and values for the discharge of a one-year-flood are often available from hydrographic services.

Assessment of channel roughness

If the program needs to calculate the water surface elevation in the analysed cross sections for the selected discharge, the hydraulic roughness has to be estimated via the formulas provided below or selected according to calibrated hydrodynamic-numerical models. Alternatively, the user may also use measured or modelled water surface elevations as input data. The channel roughness may be estimated from the grain sizes of the bed surface. In wadeable rivers, the Wolman pebble count method (Wolman, 1954) delivers fast and reliable data from the bed surface's grain size distribution. In non-wadeable rivers, Wolman pebble counts may be performed during low-flow conditions on bars close to the water edges or in areas with shallow water. A skin friction C_{fs} may be estimated via

$$\mathrm{C_{fs}^{-\frac{1}{2}}} = 8.1\left(\frac{\mathrm{H_{bf}}}{\mathrm{k_s}}\right)^{\frac{1}{6}}$$

where H_{bf} is the water depth of bankfull discharge and k_s is a roughness height given as

$$\mathrm{k_s} = 2\mathrm{d_{90}}$$

and d_{90} is the surface grain size such that 90 percent is finer (Parker, 1991; Wong, 2003; Wong and Parker, 2006; Parker et al., 2007).
The channel roughness may be increased by an additional effect of form drag. Derived from baseline data from several US-American and Britain rivers by Parker et al. (2007), the total channel resistance for natural rivers was found to amount to

$$C_f^{-\frac{1}{2}} = 3.71\left(\frac{H_{bf}}{d_{50}}\right)^{0.263}$$

Depending on the artificiality of the analysed reach, the final Chezy coefficient *C* may be increased from the skin roughness C_{fs} towards the value of C_f to account for the form drag of the channel.

Preparation of input data.
Before running the program, the following input data needs to be provided:

- Text files which include the cross section number, lateral distance and elevation for the pre-event and post-event state,

and:

- either one text file containing the discharge, roughness and slope of the channel,

or:

- text files containing water surface elevations for the cross sections at the pre- and post-event state.

The exact requirements on the format of the input files are provided with the executable (by providing example input data).

Running the program.
Clicking on the executable will start the analysis of channel characteristics for every state of every cross section. If the hydrodynamics need to be calculated by the program (if no water surface elevations were provided), the program uses the Gauckler-Manning-Strickler equation for calculating the flow velocity *v*:

$v=\frac{1}{n}R^{\frac{2}{3}}S^{\frac{1}{2}}$,

where S is the channel slope, and n is the Manning coefficient converted from the Chezy coefficient C via $n = R^{1/6}/C$.

The water level z_w is determined were v reaches the same value as the quotient of the discharge *Q* divided by the cross-sectional area *A*. Note that for every cross section, the program assumes a uniform channel geometry with the slope provided by the user. This has to be considered especially for applications to very non-uniform channel geometries and non-uniform flow. If available, the user should use measured water surface elevations or water surface elevations which were calculated by one-dimensional models.

For the water surface elevation which was calculated by the program or provided by the user, the following values are given out for further analysis:

- Lateral position of the left and right water edges x_l and x_r,
- Water surface width w,
- The cross-sectional area of the flow A, and
- the numbers of channels within the cross section.

The mean bed elevation z_{mb} is then calculated via:

$$\mathrm{z_{mb}} = \mathrm{z_w} - \frac{\mathrm{A}}{\mathrm{w}}$$

From two different states of one cross section, the following cross sectional changes, as depicted in Fig. 34, are calculated:

- Left bank accretion $= x_{l,post} - x_{l,pre}$
- Right bank accretion $= x_{r,pre} - x_{r,post}$
- Channel widening $= w_{post} - w_{pre}$
- Channel migration (positive values for migration to the right) $= (x_{l,post} - x_{lpre} - x_{r,pre} + x_{r,post})/2$
- Bed level change $= z_{mb,post} - z_{mb,pre}$
- Water level change $= z_{w,post} - z_{w,pre}$

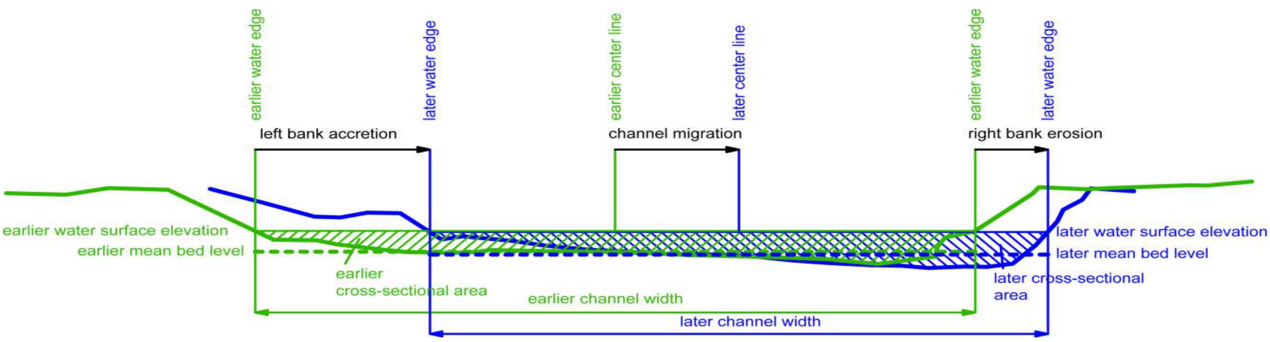


Fig. 34. Two states of a cross section and determined cross-sectional changes.

Most of the results can then be displayed with the channel evolution diagram, which was developed to provide a quick overview of the channel's lateral and vertical dynamics in one single diagram (Fig. 35).

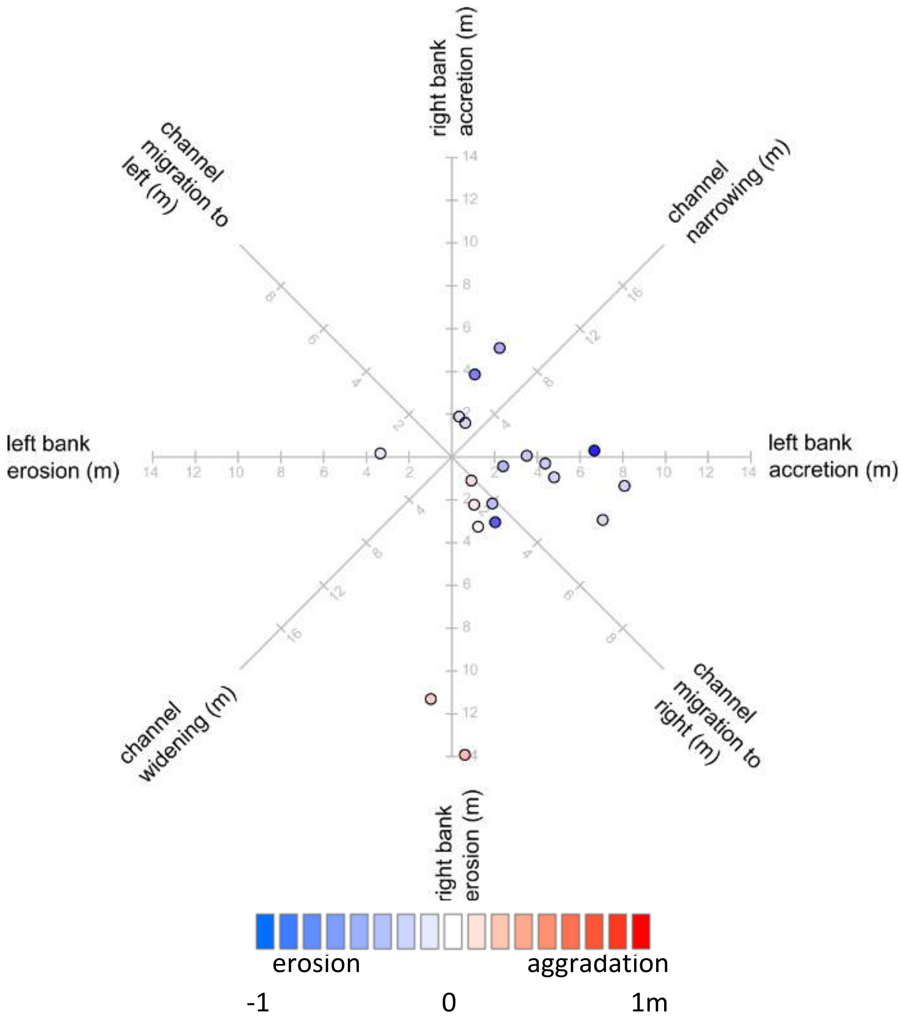
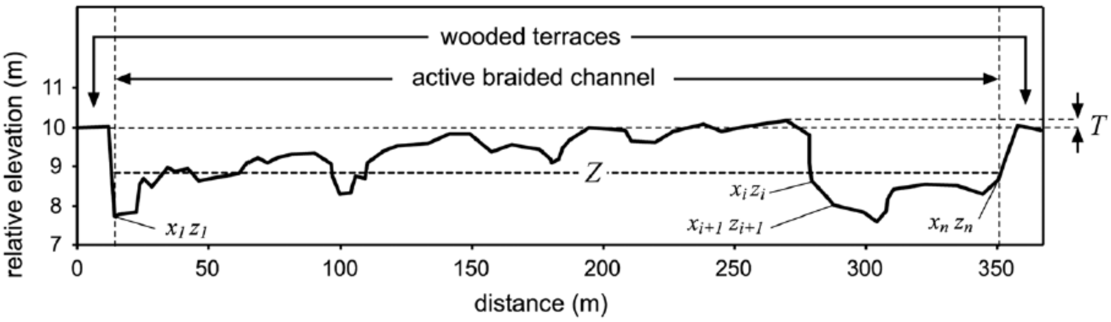


Fig. 35. The channel evolution diagram of HyMoCARES Chevo.

4.1.2. The Bed Relief Index (Liébault et al., 2013)

The macro-roughness of self-formed alluvial river channels, and especially of braided gravel-bed rivers, has been shown to covariate with channel aggradation and degradation trends, notably in laboratory experiments (Hoey and Sutherland, 1991). The Bed Relief Index (BRI), calculated as the standard deviation of elevation of the active channel along a cross-section (excluding river banks), has been shown to increase during degradation phases, and decrease during aggradation phases (Hoey and Sutherland, 1991). A normalized Bed Relief Index (BRI*; Liébault et al., 2013) is calculated as the ratio between the standard deviation of elevations in the active channel and the active channel width (Fig. 36). It has notably been shown that the BRI* is a good proxy of supply vs. transport-limited conditions for braided rivers (Liébault et al., 2013; Lallias-Tacon, 2015). Transport-limited braided rivers show lower BRI* than supply-limited ones. It could therefore be interesting to use this metrics as an indicator of the changing sediment regime of braided rivers through time, to be used as a complementary index to traditional bed-level monitoring. A tool for the automatic calculation of BRI* is available from the FluvialCorridor toolbox (**http://www.sedalp.eu/download/tools.shtml**).



$$BRI^* = \left(\frac{1}{n}\sum_{i=1}^{n}(z_i - Z)^2\right)^{0.5} / (x_n - x_i)$$

Fig. 36. Calculation of the bed relief index (Liébault et al., 2013).

4.1.3. Bed elevation frequency distribution (Redolfi et al., 2016)

The **Bed elevation frequency distribution** (Redolfi et al., 2016) is a reach-scale index that can be used as a diagnostic tool to quantify changes in the morphological trajectory of braided rivers driven by anthropogenic and natural forcing. A power law function is fitted to the bed elevation frequency distribution of an averaged cross secion:

$$b = kD^{\alpha}$$

Where b is the wetted width for a water depth D (measured in relation to the deepest point), k determines the scale of the width and the exponent α represents the shape of the averaged cross section (Fig. 37).

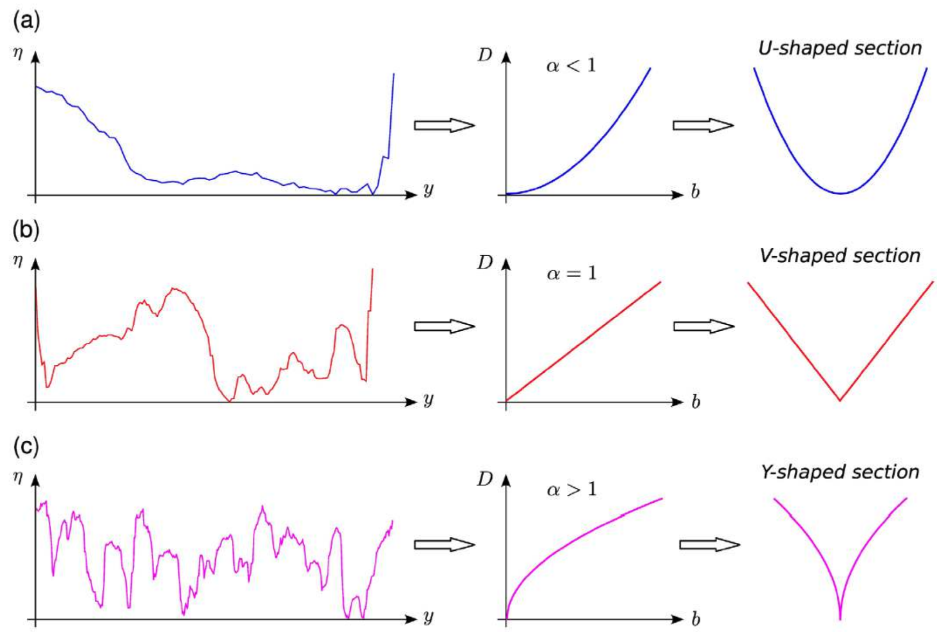


Figure 2. (left) Three characteristic cross-section types and corresponding (middle) reach-scale b(D) curve and (right) average section: (a) concave upward shape; (b) triangular shape; (c) concave downward shape, with α indicating the exponent of the power law (2).

Fig. 37. Exemplified cross section types and the corresponding exponent α of the bed elevation frequency distribution, which reflects the degree of braiding intensity (Redolfi et al., 2016).

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