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REFORM

REstoring rivers FOR effective catchment Management

Deliverable	D4.5
Title	**Fact sheets for restoration projects**
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PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Summary

This deliverable D4.5 summarizes information and experiences for thirteen river types and lists meta-data analysis results based on 844 publications.

The report starts with a summary of a literature meta-data analysis, using the REFORM river reach typology. Of the 22 REFORM river types, 12 types occurred in the database together with four combinations of 2-3 river types. In total, 11 pressure categories and 23 pressures were classified. Channelization was the most common pressure category in all river types. This is not surprising as the focus of the review was on hydromorphology. Second was habitat degradation followed closely by barriers/connectivity, bank degradation and flow alteration. In-channel habitat conditions are mostly improved by restoration with a broad spectrum over actual measures in this category. Next floodplain and river planform appeared mostly restored. Within the floodplain the attention went to reconnecting and creating existing backwaters, oxbow-lakes and wetlands. The river planform measures dealt with re-meandering, widening and re-braiding. The riparian zone, mainly the development of natural vegetation on buffer strips, also was often implemented. Hydrological measures were much less often executed.

The main component of the report deals with fact sheets and per river type provides a synthesis of restoration experiences describing best and efficient restoration practices, including promising restoration techniques and variables suited for monitoring restoration. The river typology that is being developed for the classification of fact sheets is based on an integration of four different classifications commonly used in Europe (see Appendix). Each single fact sheet consists of the paragraphs: River type name, Pressure categories/pressures, Measure categories/measures, and Monitoring scheme.

The river typology adopted for the fact sheets in this Deliverable differs from the river reach typology developed in REFORM. The relation between these typologies is not straightforward. The river typology adopted here, refers to the catchment or subcatchment setting of a river in terms of altitude, size and geology. This setting does not change in time. In contrast, the REFORM river reach typology is designed for assessing the hydromorphological functioning of individual river reaches. REFORM river reach types may change in time because they represent the response of the river reaches to processes of flow, sediment and vegetation, which can all change through time. Furthermore, river catchments or sub-catchments of a single type according to the typology used in this deliverable may contain several reaches of different REFORM types, and indeed all of the REFORM river types could potentially be found within many of the river types used in this deliverable. Notwithstanding the differences in nature, purpose and scale of these two different typologies, Table 11 presents an indication of the range of REFORM river types that might most commonly be encountered in reaches of river located within the categories of the river typology adopted in this deliverable.

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Table of Contents

REFORM
REstoring rivers FOR effective catchment Management

1 Supporting information for the fact sheets

1.1 Introduction to REFORM reach types

Deliverable 4.5 will present a synthesis of restoration experiences describing best and efficient restoration practises for different cases (combinations of hydromorphological stressors and river / catchment types) including promising restoration techniques and variables suited for monitoring restoration. This Deliverable is based upon a combination of expert knowledge and literature data.

Before the design and filling of fact sheets we performed a literature review and meta-analysis, as presented in Deliverable 1.2 on pressures. This review was based on 844 publications. In this study the first step was the translation of channel pattern defined as planform or channel pattern categories: meandering, braiding, wandering, anastomos-ing, straight; straight means channel is naturally straight, e.g. in headwater V-notched valleys) and stream type defined as stream type categories: step-pool boulder bed stream, gravel bed, mixed gravel / sand, sand-bed, loess-loam dominated, organic sub-strate dominated), into the 22 REFORM hydromorphological reach types as defined in Figure 1.

Of these 22 REFORM reach types 12 types occurred in the database together with four combinations of 2-3 reach types, one subtype and four river groups (gravel-bed river, mixed gravel/sand-bed river, organic-bed river and sand-bed river). The organic bed river is a new type not present in the REFORM typology. For 274 projects no river nor reach typological classification could be made.

We listed the types and combinations of types into a hierarchical order (Table 1). With this different hierarchical levels we could apply a literature and projects evaluatin for pressures and measures.

BED MATERIAL CALIBRE **(dominant type in bold)**	PLANFORM Braided	Island Braided	Anabranching (high energy)	Wandering	Pseudo-meandering (sinuous with alternate bars)	Sinuous - Straight	Meandering	Anabranching (low energy)
	No exposed bed material							
Entirely artificial bed						0		
	Bedrock and Colluvial Channels							
Bedrock						1		
Coarse - Mixed						2		
Mixed						3		
	Alluvial (confined single-thread)							
Boulder - Cobble						4 (Cascade)		
Boulder - Cobble						5 (Step-pool)		
Boulder - **Cobble** – Gravel						6 (Plane Bed)		
Cobble - **Gravel**						7 (Riffle-pool)		
	Alluvial (partly-confined / unconfined single thread; confined / partly-confined / unconfined transitional / multi-thread)							
Cobble - **Gravel** – Sand	8	9	10	11	12	13	14	
Fine Gravel – **Sand**	15				16	17	18	19
Fine Sand - **Silt** – Clay						20	21	22

Figure 1. REFORM reach typology.

Table 1. Hierarchical order of the REFORM reach types.

	REFORM-type	**Combined type**
Artificial river reaches	0	
Bedrock and colluvial river reaches		
Bedrock river reaches	1 (no data)	
Coarse-mixed colluvial river reaches	2 (no data)	
Mixed colluvial river reaches	3 (no data)	
Alluvial river reaches		
Alluvial confined, single-thread river reaches		
Cascade boulder river reaches	4 (no data)	
Step-pool boulder river reaches	5	
Plane bed cobble river reaches	6 (no data)	
Riffle-pool gravel river reaches	7 (no data)	
Alluvial river reaches (others)		
Mixed gravel/sand-bed river reaches		
Gravel-bed river reaches		
Braided gravel-bed river reaches	8	Braiding river reaches
Island braided gravel-bed river reaches	9 (no data)	
Anabranching high energy gravel-bed river reaches	10	Anabranching river reaches
Wandering gravel-bed river reaches	11	
Pseudo-meandering gravel-bed river reaches	12 (no data)	
Sinuous and straight gravel-bed river reach-es	13	
Meandering gravel-bed river reaches	14	Meandering river reach-es
Sand/silt/organic bed river reaches		
Sand-bed river reaches		
Braided sand-bed river reaches	15	Braiding river reaches
Pseudo-meandering sand-bed river reaches	16	
Sinuous and straight sand-bed river reaches	17	
Meandering sand-bed river reaches	18	Meandering river reach-es
Anabranching low energy sand-bed river reaches	19	Anabranching river reaches
Silt- and organic bed river reaches		
Silt-bed river reaches		
Sinuous and straight silt-bed river reaches	20	
Meandering silt-bed river reaches	21	Meandering river reach-es
Meandering loess-loam-bed river	21L	Meandering river reach-es
Anabranching low energy silt-bed river reaches	22	Anabranching river reaches
Organic-bed river reaches	23	

1.2 Metadata analysis of pressures and measures

In total, 7 hydromorphological pressure categories and 19 hydromorphological pressures were classified (Table 2).

Table 2. Listing of hydromorphological pressure categories and pressures.

Pressure category	Pressure	Comment
Water abstraction	Major pressure category: Water abstraction	Major pressure category "Water abstraction" with further list of specific major pressure categories of this category in the following
Water abstraction	Surface water abstraction	
Water abstraction	Groundwater abstraction	
Flow alteration	Major pressure category: Flow regulation	Major pressure category "Flow regulation" with further list of specific major pressure categories of this category in the following
Flow alteration	Discharge diversions and returns	
Flow alteration	Interbasin flow transfer	
Flow alteration	Hydrological regime modification including erosion due to increase in peak discharges	
Flow alteration	Hydropeaking	
Flow alteration	Impoundment	
Barriers/Connectivity	Major pressure category: River continuity	Major pressure category "River continuity" with further list of specific major pressure categories of this category in the following
Barriers/Connectivity	Artificial barriers upstream from the site	
Barriers/Connectivity	Artificial barriers downstream from the site	
Channelization	Major pressure category: Morphological alteration	Major pressure category "Morphological alterations" with further list of specific major pressure categories of this category in the following
Channelization	Channelisation / cross section alteration (e.g. deepening) including erosion due to this	
Channelization	Sedimentation	
Bank degradation	Embankments, levees or dikes	
Habitat degradation	Alteration of riparian vegetation	
Habitat degradation	Alteration of instreams habitat	
Maintenance	Sand and gravel extraction, dredging	

An general overview of the REFORM reach types and the number of projects (based on literature) with number of major pressures and pressures per project is given in Table 3.

Table 3. Overview of REFORM reach types and pressures.

Stream type	Channel pattern		Total number of		
Artificial	**Meandering**	**REFORM river type(s)**	**pro-jects**	**major pres-sures**	**- pres-sures**
Step-pool boulder bed stream	Wandering	0	6	12	18
Gravel-bed river	Braiding	5	21	53	79
Gravel-bed river	Wandering	8	17	51	74
Gravel-bed river	Straight (e.g.V-notched valley)	11	13	41	64
Gravel-bed river	Meandering	13	3	10	16
Mixed gravel / sand river	Braiding	14	132	322	501
Mixed gravel / sand river	Straight (e.g.V-notched valley)	15	4	11	18
Mixed gravel / sand river	Meandering	17	6	12	20
Sand-bed river	Anastomosing	18	66	158	253
Sand-bed river	Meandering	19	2	7	7
Organic substrate domi-nated river	Meandering	21	100	248	375
No info	Anastomosing	23	22	53	84
No info	Meandering	1, 19, 22	1	4	4
Loess-loam dominated river	No info	14, 18, 21	74	200	323
Loess-loam dominated river	Meandering	2, 21, 22	2	3	5
No info	Braiding	21L	6	13	18
Gravel-bed river	No info	8, 15	4	13	24
Mixed gravel / sand river	No info	Gravel-bed river	59	143	206
No info	No info	Mixed gravel-sand-bed river	9	21	33
Organic substrate domi-nated river	No info	no info	274	663	1028
Sand-bed river	No info	Organic-bed river	6	21	29
		Sand-bed river	17	41	53

In the first step we counted the number of pressures (Table 3, Appendix 3) per reach type. One must take into account that the number of projects per reach type varies strongly. Reach types with less than five projects will be included in all tables but will not further be discussed as the number of observations is too low. In general, most projects are under constraint of two (34%) or three (30%) pressure categories, only 13% listed one pressure category (we left 0 out as this category is based on missing information) and the maximum number of eight occurred in <1% of the projects (Appendix 4). Looking in more detail, most projects are under pressure of two (29%) or three (29%) pressures, only 2% listed one pressure and the maximum number of 14 occurred in <1% of the projects (Table 5). The mutual differences between reach types in number of pressure categories and pressures are very low (Table 4 and Appendix 3).

Table 4. Percentage of the number of pressures present per REFORM reach type.

	Projects	Number of pressures														
REFORM reach types	**(n)**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
0	6	0	0	33	33	33	0	0	0	0	0	0	0	0	0	0
5	21	0	5	29	14	19	19	10	0	0	5	0	0	0	0	0
8	17	0	0	18	18	29	12	12	6	0	0	6	0	0	0	0
11	13	0	0	23	31	8	8	0	8	15	0	0	0	0	0	8
13	3	0	0	0	33	33	0	0	0	0	33	0	0	0	0	0
14	132	3	1	9	37	25	11	8	5	1	0	0	0	1	0	0
15	4	0	0	0	50	25	0	0	0	25	0	0	0	0	0	0
17	6	0	0	33	33	17	0	17	0	0	0	0	0	0	0	0
18	66	3	2	11	36	20	14	8	3	3	2	0	0	0	0	0
19	2	0	0	0	50	50	0	0	0	0	0	0	0	0	0	0
21	100	4	0	22	23	23	15	6	2	0	5	0	0	0	0	0
23	22	0	9	0	32	36	14	5	0	5	0	0	0	0	0	0
10, 19, 22	1	0	0	0	0	100	0	0	0	0	0	0	0	0	0	0
14, 18, 21	74	4	3	5	28	20	16	9	4	5	0	1	1	1	0	0
20, 21, 22	2	0	0	50	50	0	0	0	0	0	0	0	0	0	0	0
21L	6	0	0	33	33	33	0	0	0	0	0	0	0	0	0	0
8, 15	4	0	0	0	25	0	0	25	25	25	0	0	0	0	0	0
Gravel-bed river reach	59	10	5	14	7	41	15	5	0	3	0	0	0	0	0	0
Mixed gravel-sand-bed river reach	9	0	0	11	44	22	11	11	0	0	0	0	0	0	0	0
no info	17	7	4	23	18	12	16	8	4	3	1	2	0	0	0	0
Organic-bed river reach	6	0	0	0	0	67	17	0	0	17	0	0	0	0	0	0
Sand-bed river reach	274	6	6	12	41	24	6	6	0	0	0	0	0	0	0	0
average		*2*	*2*	*15*	*29*	*29*	*8*	*6*	*3*	*5*	*2*	*0*	*0*	*0*	*0*	*0*
stdev		*3*	*3*	*14*	*15*	*22*	*7*	*7*	*6*	*8*	*7*	*1*	*0*	*0*	*0*	*2*

Channelization is the most common pressure category in all river reach types (Table 5 and 6). Second was habitat degradation followed closely by barriers/connectivity, bank degradation and flow alteration.

Table 5. Percentage of projects in which a major pressure category was identified per REFORM reach type.

				Pressure category						
REFORM reach type(s)	**projects (n)**	**major pressures (n)**	**pressures (n)**	**Water abstraction**	**Flow alteration**	**Barriers/ Connectivity**	**Channelization**	**Bank degradation**	**Habitat degradation**	**Maintenance**
0	6	12	18	11	6	17	39	6	17	6
5	21	53	79	5	30	18	24	5	14	1
8	17	51	74	0	9	19	38	14	18	3
11	13	41	64	3	17	13	36	6	20	2
13	3	10	16	0	13	19	44	6	13	0
14	132	322	501	2	13	11	43	7	21	0
15	4	11	18	0	11	22	44	11	11	0
17	6	12	20	0	25	0	65	5	5	0
18	66	158	253	1	12	6	49	8	20	1
19	2	7	7	0	14	0	29	29	29	0
21	100	248	375	1	9	5	46	11	22	2
23	22	53	84	0	8	11	40	7	26	0
10, 19, 22	1	4	4	0	0	25	25	25	25	0
14, 18, 21	74	200	323	5	16	10	36	8	16	1
20, 21, 22	2	3	5	0	20	0	80	0	0	0
21L	6	13	18	0	0	0	61	11	22	0
8, 15	4	13	24	0	21	29	38	8	4	0
Gravel-bed river	59	143	206	1	6	10	45	15	21	0
Mixed gravel-sand-bed river	9	21	33	0	0	9	52	15	21	3
Sand-bed river	17	41	53	0	11	6	43	15	21	2
Organic-bed river	6	21	29	0	7	10	41	21	21	0
no info	274	663	1028	2	13	23	36	8	13	3
average				*1*	*12*	*12*	*43*	*11*	*17*	*1*
stdev				*3*	*8*	*9*	*13*	*7*	*7*	*1*

Table 6. Percentage of projects (number of projects is given in Table 4) in which a pressure was identified within a pressure category per REFORM reach type.

Pressure category	**Water abstraction**			**Flow alteration**							**Barriers/ Connectivity**			**Channelization**			**Habitat degradation**		
REFORM river types	**% subdivded**	**Surface water abstraction**	**Groundwater abstraction**	**% subdivded**	**Discharge diversions and returns**	**Interbasin flow transfer**	**Hydrological regime modification**	**Hydropeaking**	**Flush flow**	**Impoundment**	**% subdivded**	**Artificial barriers upstream**	**Artificial barriers downstream**	**% subdivded**	**Channelisation / cross section alteration**	**Sedimentation**	**% subdivded**	**Alteration of riparian vegetation**	**Alteration of instreams habitat**
0	50	100	0	100	0	0	0	0	0	100	67	50	50	29	100	0	100	67	33
5	50	0	100	42	40	10	20	0	0	30	36	40	60	32	83	17	100	45	55
8	0	0	0	29	0	0	0	50	0	50	57	25	75	43	92	8	62	13	88
11	50	100	0	55	17	0	50	33	0	0	50	50	50	43	90	10	85	27	73
13	0	0	0	0	0	0	0	0	0	0	67	50	50	57	75	25	100	0	100
14	50	50	50	55	14	0	39	6	3	39	63	53	47	44	85	15	98	31	69
15	0	0	0	50	100	0	0	0	0	0	50	50	50	50	50	50	100	50	50
17	0	0	0	60	0	0	33	0	0	67	0	0	0	54	86	14	0	0	0
18	50	100	0	50	0	0	67	0	7	27	63	60	40	50	81	19	100	30	70
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	0
21	50	100	0	56	0	11	50	6	6	28	59	60	40	44	82	18	100	34	66
23	0	0	0	43	0	0	67	0	0	33	67	50	50	44	100	0	100	41	59
10, 19, 22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14, 18, 21	47	63	38	60	16	6	44	6	6	22	58	63	37	44	84	16	100	38	62
20, 21, 22	0	0	0	100	0	0	0	0	0	100	0	0	0	50	100	0	0	0	0

Pressure category	**Water abstraction**			**Flow alteration**							**Barriers/ Connectivity**			**Channelization**			**Habitat degradation**		
REFORM river types	**% subdivded**	**Surface water abstraction**	**Groundwater abstraction**	**% subdivded**	**Discharge diversions and returns**	**Interbasin flow transfer**	**Hydrological regime modification**	**Hydropeaking**	**Flush flow**	**Impoundment**	**% subdivded**	**Artificial barriers upstream**	**Artificial barriers downstream**	**% subdivded**	**Channelisation / cross section alteration**	**Sedimentation**	**% subdivded**	**Alteration of riparian vegetation**	**Alteration of instreams habitat**
21L	0	0	0	0	0	0	0	0	0	0	0	0	0	45	100	0	100	0	100
8, 15	0	0	0	40	50	0	50	0	0	0	57	75	25	56	80	20	100	0	100
Gravel-bed river	50	100	0	54	0	0	71	14	0	14	40	50	50	46	86	14	100	11	89
Mixed gravel / sand-bed river	0	0	0	0	0	0	0	0	0	0	67	50	50	47	88	13	100	43	57
Sand-bed river	0	0	0	17	0	0	0	0	0	100	67	50	50	39	100	0	73	13	88
Organic-bed river	0	0	0	50	0	0	0	100	0	0	33	0	100	50	100	0	83	0	100
no info	53	50	50	42	30	2	38	2	0	29	56	51	49	43	82	18	84	41	59
average		*30*	*11*		*12*	*1*	*24*	*10*	*1*	*29*		*38*	*40*		*79*	*12*		*27*	*60*
stdev		*43*	*26*		*24*	*3*	*27*	*24*	*2*	*34*		*25*	*26*		*28*	*12*		*26*	*34*

Ten measure categories and 52 measures were listed for the analysis (Table 8). In-channel habitat conditions are mostly improved by restoration with a broad spectrum over actual measures in this category (Table 7). The three most important ones were 'remove bank fixation', 'recruitment or placement of large wood', and çreate artificial gravel bar or riffle' (Table 8). Next floodplain and river planform appeared mostly restored (Table 7). Within the floodplain the attention went for reconnecting and creating existing backwaters, oxbow-lakes, wetlands (Table 8). The river planform measures dealt with re-meandering, widening and re-braiding. The riparian zone, mainly the development of natural vegetation on buffer strips, also was often implemented. Hydrological measures were much less often executed (Table 8).

Table 7. Number of measures per main category of measures per REFORM reach type.

REFORM reach type	**Projects (n)**	**Major measures (n)**	**Measures (n)**	**Water flow quantity**	**Sediment quantity**	**Flow dynamics**	**Longitudinal connectivity**	**In-channel habitat conditions**	**Riparian zone**	**River planform**	**Floodplain**	**Others**
0	6	13	17	0	0	6	6	47	6	12	12	12
5	21	38	49	6	0	12	6	37	8	14	8	8
8	17	36	56	0	2	2	2	29	0	46	13	7
11	13	28	40	8	5	3	10	25	3	25	18	5
13	3	4	13	0	0	0	0	69	0	31	0	0
14	132	303	441	4	2	3	5	40	11	12	18	5
15	4	13	23	4	4	0	13	30	0	22	22	4
17	6	12	18	0	0	0	0	11	0	39	44	6
18	66	158	221	4	2	1	6	43	10	14	17	3
19	2	2	2	0	0	0	0	0	0	0	100	0
21	100	251	402	7	2	3	4	34	8	12	28	2
23	22	60	95	7	0	0	5	45	12	15	16	0
1, 19, 22	1											
14, 18, 21	74	164	249	5	1	3	8	34	9	18	16	6
2, 21, 22	2	4	4	0	0	0	0	0	0	50	50	0
21L	6	13	20	5	0	0	0	30	5	30	30	0
8, 15	4	6	8	0	0	0	25	13	0	13	38	13
Gravel-bed river	59	160	220	0	1	0	6	43	5	21	8	15
Mixed gravel / sand-bed river	9	15	21	0	5	0	5	43	10	10	24	5
no info	274	575	758	2	2	3	11	31	8	12	15	17
Organic-bed river	6	21	39	0	0	0	3	41	0	33	10	13
Sand-bed river	17	32	38	3	3	3	8	34	0	13	21	16
			average	2.6	1.4	1.9	5.9	32.3	4.5	21.0	24.2	6.5
			stdev	2.9	1.7	2.9	5.8	16.2	4.5	12.8	21.2	5.7

Table 8. Number of measures per REFORM reach type.

	REFORM reach type		0	5	8	11	13	14	15	17	18	19	21	23	10, 19, 22	14, 18, 21	20, 21, 22	21L	8, 15	Gravel-bed river	Mixed gravel-sand-bed river	no info	Organic-bed river	Sand-bed river
	Number of projects		6	21	17	13	3	132	4	6	66	2	100	22	1	74	2	6	4	59	9	274	6	17
Measure category	**Measure**																							
Water flow quantity		87		3		2		16	1		8		21	7		11		1		1		15		1
	Reduce water surface water abstraction without return	4									1		2									1		
	Improve water retention (e.g. on floodplain, urban areas)	59		1		1		12	1		7		15	6		9		1		1		4		1
	Reduce groundwater abstraction	6		1				2			1					1						1		
	Improve/create water storage (e.g. polders)	7				1		3					1									2		
	Increase minimum flow (to generally increase discharge in a reach or to improve flow dynamics)	16		1		1		2					5	1		1						5		
	Water diversion and transfer to improve water quantity	3														1						2		

	REFORM reach type		0	5	8	11	13	14	15	17	18	19	21	23	10, 19, 22	14, 18, 21	20, 21, 22	21L	8, 15	Gravel-bed river	Mixed gravel-sand-bed river	no info	Organic-bed river	Sand-bed river
	Number of projects		6	21	17	13	3	132	4	6	66	2	100	22	1	74	2	6	4	59	9	274	6	17
Measure category	**Measure**																							
	Recycle used water (off-site measure to reduce water consumption)	4											3									1		
	Reduce water consumption (other measures than recycling used water)	1											1									0		
Sediment quantity		44			1	2		5	1		3		8			3				2	1	17		1
	Add/feed sediment (e.g. downstream from dam)	13			1			1					2			2						6		1
	Reduce undesired sediment input (e.g. from agricultural areas or from bank erosion other than riparian buffer strips!)	8							1		2		2			1				1	1	0		
	Prevent sediment accumulation in reservoirs	1						1														0		

	REFORM reach type		0	5	8	11	13	14	15	17	18	19	21	23	10, 19, 22	14, 18, 21	20, 21, 22	21L	8, 15	Gravel-bed river	Mixed gravel-sand-bed river	no info	Organic-bed river	Sand-bed river
	Number of projects		6	21	17	13	3	132	4	6	66	2	100	22	1	74	2	6	4	59	9	274	6	17
Measure category	**Measure**																							
	Improve continuity of sediment transport (e.g. manage dams for sediment flow)	9				1		2			1		1									4		
	Trap sediments (e.g. building sediment traps to reduce washload)	13						3			1		4							1		4		
	Reduce impact of dredging	3				1																2		
Flow dynamics		60	1	6	1	1		12			2		10			7						19		1
	Establish environmental flows / naturalise flow regimes (does focus on discharge variability)	36		5	1			9			1		4			5						10		1
	Modify hydropeaking	7		1				3					1			1						1		
	Increase flood frequency and duration in riparian zones or floodplains	11				1		1			1		3			1						4		
	Reduce anthropogenic flow peaks	6						1					2									3		

	REFORM reach type		0	5	8	11	13	14	15	17	18	19	21	23	10, 19, 22	14, 18, 21	20, 21, 22	21L	8, 15	Gravel-bed river	Mixed gravel-sand-bed river	no info	Organic-bed river	Sand-bed river
	Number of projects		6	21	17	13	3	132	4	6	66	2	100	22	1	74	2	6	4	59	9	274	6	17
Measure category	**Measure**																							
	Shorten the length of impounded reaches	3	1										1									1		
	Favour morphogenic flows (could also be considered a measure to improve planform or in-channel habitat conditions	3																				3		
Longitiudinal connectivity		142	1	4	1	3		16	1		11		12	5		10			1	11	1	62	1	2
	Install fish pass, bypass, side channel for upstream migration	32				1		2			2		1			4			1	2		18		1
	Install facilities for downstream migration (including fish friendly turbines)	25				1		3								4			1	0		16		
	Manage sluice, weir, and turbine operation for fish migration	18		1				1	1		2		5	1		5						1		1
	Remove barrier (e.g. dam or weir)	103	1	2	1	2		13	1		9		8	4		6				11	1	42	1	1

	REFORM reach type		**0**	**5**	**8**	**11**	**13**	**14**	**15**	**17**	**18**	**19**	**21**	**23**	**10, 19, 22**	**14, 18, 21**	**20, 21, 22**	**21L**	**8, 15**	**Gravel-bed river**	**Mixed gravel-sand-bed river**	**no info**	**Organic-bed river**	**Sand-bed river**
	Number of projects		6	21	17	13	3	132	4	6	66	2	100	22	1	74	2	6	4	59	9	274	6	17
Measure category	**Measure**																							
	Modify or remove culverts, syphons, piped streams	13						3	1		1		2			1						5		
In-channel habitat conditions		543	4	9	9	6	3	99	3	1	53		64	18		46		3	1	54	6	148	6	10
	Remove bed fixation	76	1	1			1	22			13		17	2		8		1			2	8		
	Remove bank fixation	141	1	1	7	3		24			12		12	2		13		1		24	2	29	6	4
	Remove sediment (e.g. mud from groin fields)	30			1			5	1		8		5			3				1		6		
	Add sediment (e.g. gravel)	100	1	2	1	1	1	18		1	10		13	7		8		1		10	1	24		1
	Manage aquatic vegetation (e.g. mowing)	35	1			2	2	2			2		3	4		2				1		16		
	Remove or modify in-channel hydraulic structures (e.g. groins, bridges)	33			1			10	1		4		5			4						7		1
	Creating shallows near the bank	105		1	1	2		20	1		10		11	2		12		2	1	21		14	6	1

	REFORM reach type		**0**	**5**	**8**	**11**	**13**	**14**	**15**	**17**	**18**	**19**	**21**	**23**	**10, 19, 22**	**14, 18, 21**	**20, 21, 22**	**21L**	**8, 15**	**Gravel-bed river**	**Mixed gravel-sand-bed river**	**no info**	**Organic-bed river**	**Sand-bed river**
	Number of projects		6	21	17	13	3	132	4	6	66	2	100	22	1	74	2	6	4	59	9	274	6	17
Measure category	**Measure**																							
	Recruitment or placement of large wood	126	1	2	2			18	1		11		23	8		11		1		17	1	25	2	3
	Boulder placement	109	2	4	1		2	13		1	6		12	7		12				11		36	2	
	Initiate natural channel dynamics to promote natural regeneration	112		1	2	1		22	1		5		27	10		6				1		35		1
	Create artificial gravel bar or riffle	122	1	6		1	3	23	2		13		9	1		15				8	3	35		2
Riparian zone		212	1	4	2	2		48			21		30	11		20		1		11	3	58		
	Develop buffer strips to reduce nutrient input	18						2			3		4	3		2						4		
	Develop buffer strips to reduce fine sediment input	13						2			2		2			3				2		2		
	Develop natural vegetation on buffer strips (other reasons than nutrient or sediment input, e.g. shading, organic matter input)	183	1	4		1		44			17		26	8		18		1		9	2	52		

	REFORM reach type		0	5	8	11	13	14	15	17	18	19	21	23	10, 19, 22	14, 18, 21	20, 21, 22	21L	8, 15	Gravel-bed river	Mixed gravel-sand-bed river	no info	Organic-bed river	Sand-bed river
	Number of projects		6	21	17	13	3	132	4	6	66	2	100	22	1	74	2	6	4	59	9	274	6	17
Measure category	**Measure**																							
River planform		313	2	7	17	8	1	43	4	5	28		35	8		31	2	4	2	32	1	72	6	5
	Re-meander water course (actively changing planform)	148		5	3	1		20	2	5	17		18	4		17	2	2		6		39	5	2
	Widening or re-braiding of water course (actively changing planform)	114			12	6	1	14	1		6		7	4		10		2		26		18	6	1
	Shallow water course (actively increasing level of channel-bed)	53		1	3		1	6			4		9	3		5		2		12		6	1	
	Narrow over-widened water course (actively changing width)	25				1		1	2	2	2		3			1				3	1	7		2
	Create low-flow channels in over-sized channels	38	2		3	2		3			2		5	1		4			1			14	1	
	Allow/initiate lateral channel migration (e.g. by removing bank fixation and adding large wood)	30		1	5		1	8					5	1		6						3		

	REFORM reach type		0	5	8	11	13	14	15	17	18	19	21	23	10, 19, 22	14, 18, 21	20, 21, 22	21L	8, 15	Gravel-bed river	Mixed gravel-sand-bed river	no info	Organic-bed river	Sand-bed river
	Number of projects		6	21	17	13	3	132	4	6	66	2	100	22	1	74	2	6	4	59	9	274	6	17
Measure category	**Measure**																							
	Create secondary floodplain on present low level of channel bed	8					1				1		2	1		1					1	1		
Floodplain		320	2	3	5	4		51	3	5	30	2	63	11	1	25	2	4	2	18	4	76	3	6
	Reconnect existing backwaters, oxbow-lakes, wetlands	162		2	4	4		23	2	4	11	2	38	4	1	9		3	2	10	1	37	3	2
	Create semi-natural / artificial backwaters, oxbow-lakes, wetlands	115	2	1	1			24	1	2	6		33	1		13	2	2		1		23	1	2
	Lowering embankments, levees or dikes to enlarge inundation and flooding	64			1			11	1	2	8		15	4		6		1	1	3		11		
	Back-removal of embankments, levees or dikes to enlarge the active floodplain area	23			1	1		3			2		6	2							2	4		2

	REFORM reach type		**0**	**5**	**8**	**11**	**13**	**14**	**15**	**17**	**18**	**19**	**21**	**23**	**10, 19, 22**	**14, 18, 21**	**20, 21, 22**	**21L**	**8, 15**	**Gravel-bed river**	**Mixed gravel-sand-bed river**	**no info**	**Organic-bed river**	**Sand-bed river**
	Number of projects		6	21	17	13	3	132	4	6	66	2	100	22	1	74	2	6	4	59	9	274	6	17
Measure category	**Measure**																							
	Remove embankments, levees or dikes or other engineering structures that impede lateral connectivity	31				1		3	1		1		7	3	1	3				2	1	8		
	Remove vegetation	84		1		1		16			10		14	1		9				2	1	27		2
Others	Others	243	2	4	4	2		22	1	1	6		8			15			1	34	1	131	5	6

2. Design of the fact sheets

2.1 Introduction

An extended reach typology with 22 reach types was developed in REFORM (Figure 1). Channel type is a core component of the final stage of the hierarchical assessment framework, in which current channel type is compared to the typologies for floodplains and groundwater - surface water interactions and the changes that have occurred over time at wider spatial scales to assess current reach condition, sensitivity and trajectories of change. The hierarchical framework leads practitioners through a series of steps to delineate their river into spatial units; characterise the relevant hydrological, geomorphological and ecological characteristics at each scale; and assess the current hydromorphological condition of the river and its sensitivity to change.

The extended REFORM reach typology can be grouped into 7 overarching units (Table 9)

Table 9. REFORM reach typology condensed in seven overarching units.

	REFORM macro-class	REFORM extended reach typology	Substrate	Planform
REF1	1. Bedrock and colluvial	1, 2, 3	bedrock, coarse mixed	sinuous-straight
REF2	2. Alluvial, steep, confined single-thread, very coarse bed sediment	4, 5	boulder, cobble	cascade, step-pool
REF3	3. Alluvial, steep, confined single-thread, coarse bed sediment	6, 7	boulder, cobble, gravel	plain bed, riffle-pool
REF4	4. Alluvial, partly confined/unconfined multi-thread or transitional, coarse to fine bed sediment	8, 9, 10, 11,15	fine gravel, sand	(island) braided, anabranching (high energy), wandering
REF5	5. Alluvial, partly confined/unconfined single-thread, coarse bed sediment	12, 13, 14	fine gravel, sand	(pseudo-)meandering, sinuous-straight
REF6	6. Alluvial, partly confined/unconfined single-thread, fine to very fine bed sediment	16, 17, 18, 20, 21	fine gravel, sand, silt, clay	(pseudo-)meandering, sinuous-straight
REF7	7. Alluvial, partly confined/unconfined anabranching, fine to very fine bed sediment	19, 22	fine gravel, sand, silt, clay	anabranching (low energy)

The European Topic Centre recently asked NIVA to revise the CIS river typology (Table 10). Here 20 river types were defined and linked to different broad European and national river typologies.

Table 10. River typology European Topic Centre (ETC 2015).

Broad river type code	Broad river type name	Altitude (masl)	Catch-ment area (km2)	Geology	number of national types	number of WBs	% of WBs
ETC1	Very large rivers (all Europe)	any	>10000	any (usually mixed)	54	827	1,0
ETC2	Lowland, Siliceous, Medium-Large	≤200	100-10000	Siliceous	24	1139	1,4
ETC3	Lowland, Siliceous, Very small-Small	≤200	≤100	Siliceous	30	7302	8,9
ETC4	Lowland, Calcareous or Mixed, Medium-Large	≤200	100-10000	Calcareous/Mixed	67	2872	3,5
ETC5	Lowland, Calcareous or Mixed, Very small-Small	≤200	≤100	Calcareous/Mixed	47	14137	17,1
ETC6	Lowland, Organic and Siliceous	≤200	<10000	Organic and Siliceous	18	6193	7,5
ETC7	Lowland, Organic and Calcareous/Mixed	≤200	<10000	Organic and Calcareous/Mixed	9	336	0,4
ETC8	Mid altitude, Siliceous, Medium-Large	200-800	100-10000	Siliceous	41	3051	3,7
ETC9	Mid altitude, Siliceous, Very small-Small	200-800	≤100	Siliceous	37	8627	10,5
ETC10	Mid altitude, Calcareous or Mixed, Medium-Large	200-800	100-10000	Calcareous/Mixed	61	1797	2,2
ETC11	Mid altitude, Calcareous or Mixed, Very small-Small	200-800	≤100	Calcareous/Mixed	48	7663	9,3
ETC12	Mid-altitude, Organic and siliceous	200-800	<10000	Organic and Siliceous	8	3290	4,0
ETC13	Mid-altitude, Organic and Calcareous/Mixed	200-800	<10000	Organic and Calcareous/Mixed	6	154	0,2
ETC14	Highland (all Europe), Siliceous, incl. Organic (humic)	>800	<10000	Siliceous	16	1525	1,8
ETC15	Highland (all Europe), Calcareous/Mixed	>800	<10000	Calcareous/Mixed	17	2227	2,7
ETC16	Glacial rivers (all Europe)	>200	<10000	any	16	3251	3,9
ETC17	Mediterranean, Lowland, Medium-Large, perennial	≤200	100-10000	any	16	941	1,1
ETC18	Mediterranean, Mid altitude, Medium-Large, perennial	200-800	100-10000	any	13	615	0,7
ETC19	Mediterranean, Very small-Small, perennial	<800	≤100	any	21	1942	2,4
ETC20	Mediterranean, Temporary/Intermittent streams	any	<1000	any	26	3549	4,3

There is a link between the REFORM reach typology and the ETC types (Table 11).

Table 11. Link between REFORM rivertypes, planform pattern, bed material size and ETC type.

REFORM river type	Planform pattern	Bed material size (**dominant size**)	ETC
Bedrock and Colluvial channels			
1	Straight-sinuous	**Bedrock**	9, 11, 14 - 16, 19, 20
2	Straight-sinuous	**Coarse - mixed**	9, 11, 14 - 16, 19, 20
3	Straight-sinuous	**Mixed**	9, 11, 14 - 16, 19, 20
Alluvial channels			
4	Straight-sinuous	**Boulder**	9, 11, 14, 15, 16, 19, 20
5	Straight-sinuous	**Boulder**-Cobble	9, 11, 14, 15, 16, 19, 20
6	Straight-sinuous	Boulder-**Cobble**-Gravel	9, 11, 14, 15, 16, 19, 20
7	Straight-sinuous	Cobble-**Gravel**	9, 11, 14, 15, 16, 19, 20
8	Braided	**Gravel**-Sand	8 - 13, 16, 18 - 20
9	Island-braided	**Gravel**-Sand	8 - 13, 16, 18 - 20
10	Anabranching (high energy)	**Gravel**-Sand	8 - 13, 18, 19
11	Wandering	**Gravel**-Sand	8 - 13, 16, 18 - 20
12	Pseudo-meandering	**Gravel**-Sand	8 - 13, 18 - 20
13	Straight-sinuous	**Gravel**-Sand	8 - 13, 18 - 20
14	Meandering	**Gravel**-Sand	8 - 13, 18 - 20
15	Braided	Fine gravel-**Sand**	1 - 7; 17
16	Pseudo-meandering	Fine gravel-**Sand**	1 - 7; 17
17	Straight-sinuous	Fine gravel-**Sand**	1 - 7; 17
18	Meandering	Fine gravel-**Sand**	1 - 7; 17
19	Anabranching (low energy)	Fine gravel-**Sand**	1 - 7; 17
20	Straight-sinuous	Fine sand-**Silt**-Clay	1 - 7; 17
21	Meandering	Fine sand-**Silt**-Clay	1 - 7; 17
22	Anabranching (low energy)	Fine sand-**Silt**-Clay	1 - 7; 17

2.2 Adapted REFORM reach typology used in the fact sheets

The typology that is being developed for the classification of fact sheets is mainly based on the REFORM reach typology with addition of size, geographical and altitude classes as used in the typology published by the European Topic Centre. The fact sheets comprises 14 river reach types (Table 12) based upon the combination of planform, substrates, size, geographical area and altitude of the river's catchment. There is a link of the fact sheet types to the ETC types to facilitate water managers (a more extended table with links can be found in the appendix). Because the ETC types are linked to national river types. Apart from recognisability for water managers, the typology is high scaled (in other words consists of a limited number of river types) which meets our objectives. The fact sheets will not be composed as a cook book but are intended to reflect a way of reasoning.

Table 12. The river typology with main river types that are used in the fact sheets.

		REFORM major classes	REFORM hymo classification	European Topic Centre 2015
	High energy, highland rivers			
1	Small, sinuous-straight, highland rivers with bedrock-coarse mixed sediments	REF1	1, 2, 3	ETC14, 15, 20
2	Medium-Large, sinuous-straight, highland rivers with bedrock-coarse mixed sediments	REF1	1, 2, 3	ETC14, 15, 20
3	Small, cascade, step-pool/plain bed, riffle-pool, highland rivers with (very) coarse sediments	REF2, REF3	4, 5, 6, 7	ETC14, 15, 20
4	Medium-Large, cascade, step-pool/plain bed, riffle-pool, highland rivers with (very) coarse sediments	REF2, REF3	4, 5, 6, 7	ETC14, 15, 20
	Medium energy, mid altitude rivers with coarse to fine sediments			
5	Small, single-thread or multi-thread, mid altitude rivers	REF4, REF5	8-15	ETC9, 11, 12, 13, 19, 20
6	Medium-Large, single-thread or multi-thread, mid altitude rivers	REF4, REF5	8-15	ETC8, 10, 12, 13, 18
7	As 6, but specific for Boreal rivers			
	Low energy, lowland rivers with fine to very fine bed sediment			
8	Small, single-thread, lowland rivers	REF6	16, 17, 18, 20, 21	ETC3, 5, 6, 7, 19, 20
9	Medium-Large, single-thread, lowland rivers	REF6	16, 17, 18, 20, 21	ETC2, 4, 6, 7, 17
10	Small, anabranching, lowland rivers	REF7	19, 22	ETC3, 5, 6, 7
11	Medium-Large, anabranching, lowland rivers	REF7	19, 22	ETC2, 4, 6, 7
	Others			

		REFORM major classes	REFORM hymo classification	European Topic Centre 2015
12	Very large rivers (all Europe)	REF6, REF7	16, 17, 18, 20, 21, 19, 22	ETC1
13	Glacial rivers (all Europe)	REF1, REF2, REF3	1, 2, 3, 4, 5, 6, 7	ETC16

2.3 Fact sheet design: general outline

In total, we describe 13 fact sheets classified according to the 13 river types (Table 3). The information in the fact sheets is restoration case based literature and expert knowledge. Terms are not explained as the fact sheet become part of the WIKI in which all technical terms and measures and pressures are defined and explained.

River type name:

Text block: Each fact sheet starts with a short description of the river type.

Pressure categories/pressures

Text block: Short description of the dominant (most common in this river type) pressure categories and/or pressures.

Matrix: In a matrix the pressure categories/pressures are scored according to the stress they impose:

- No = no pressure/stress
- Low = low pressure/stress in comparison to other pressures within this river type
- Moderate = moderate pressure/stress in comparison to other pressures within this river type
- High = high pressure/stress in comparison to other pressures within this river type

Text block: Problems and constraints caused by the main pressure categories and their interactions.

Measure categories/measures

Text block: Short description of the dominant (most common in this river type) measure categories and/or measures.

Matrix: In a matrix the measure categories/measures are scored according to:

- Relevance
- Effect in-stream
- Effect floodplain
- Costs

Each matrix cell, except for the column costs, is scored according to the following score:

- No = no relevance or effect
- Low = low relevance or effect of the measure in comparison to other measures within this river type
- Moderate = moderate relevance or effect of the measure in comparison to other measures within this river type
- High = high relevance or effect of the measure in comparison to other measures within this river type

In the matrix an extra column is added to indication a prioritisation of measures according to the scale:

- Low = low priority
- Moderate = moderate priority

- High = high priority

Text block: Promising measures, novel measures and measure combinations. This is the most important text block in which guidance for future restoration is provided.

Monitoring scheme

Text block: Short description of the best approach to design a monitoring scheme for this river type.

Matrix: In a matrix the variables are scored according to:
- Effect-size in-stream
- Effect-size riparian
- Effect-size floodplain

Each matrix cell is scored according to the following score:
- No = no relevance
- Low = low relevance in comparison to other variables within this river type
- Moderate = moderate relevance in comparison to other variables within this river type
- High = high relevance or effect in comparison to other variables within this river type

Text block: Here a general advice describes the major items and ideas for an effective monitoring scheme.
The variable groups within the monitoring matrix are:
River hydrology
In-stream hydraulics
Floodplain morphology
In-channel morphology
- Profile (longitudinal, transversal)
- Meso-/micro-structures

Chemistry
- Nutrients
- Toxicants
- Others

Biology
- Algae
- Macrophytes
- Macroinvertebrates
- Fish
- Floodplain/riparian vegetation
- Terrestrial fauna

2.4 *Fact sheet design: pressures*

Drivers are those anthropogenic activities that may have an effect on the environment, such as: agriculture, urbanization, industry, water supply, navigation (and transport in general), fisheries, recreation and flood protection.

Pressures (categories) are the direct effect of the driver, for example, an effect that causes a change in flow conditions or a change in water quality. Stressors point to variables directly responsible for an effect.

In REFORM the pressure categories and main pressures are based on an extended literature survey (Table 13). In the fact sheets the pressures are scored in comparison to other pressures within the river type and not in comparison to other types / regions. Scores are not based on the assumption that all pressures are present but rather reflect the generic situation. This makes a certain bias unavoidable as pressure situations can differ between regions. For example, point sources are still the main pressure in Eastern Europe while they have a much lower impact in Central Europe since water quality has substantially improved.

Table 13. Pressure categories and pressures.

Pressure category	**Pressure**
Point sources	
Diffuse sources	
Water abstraction	
	Surface water abstraction
	Groundwater abstraction
Flow alteration	
	Discharge diversions and returns
	Interbasin flow transfer
	Hydrological regime modification including erosion due to increase in peak discharges
	Hydropeaking
	Flush flow
	Impoundment
Barriers/Connectivity	
	Artificial barriers upstream from the site
	Artificial barriers downstream from the site
Channelization	
	Channelization / cross section alteration (e.g. deepening) including erosion due to this
	Sedimentation
Bank degradation	
Habitat degradation	
	Alteration of riparian vegetation
	Alteration of instreams habitat
Maintenance	
Exotic species	

2.5 Fact sheet design: measures

In total, 11 measure categories and 55 measures are included (Table 14). A more extensive explanation can be found in Appendix 1.

Table 14. Measure categories and measures.

Measure category	**Measure**
Decrease point source pollution	
Decrease diffuse nutrient or pollution input (other than buffer strips!)	
Water flow quantity	
	Reduce water surface water abstraction without return
	Improve water retention (e.g. on floodplain, urban areas)
	Reduce groundwater abstraction
	Improve/create water storage (e.g. polders)
	Increase minimum flow (to generally increase discharge in a reach or to improve flow dynamics)
	Water diversion and transfer to improve water quantity
	Recycle used water (off-site measure to reduce water consumption)
	Reduce water consumption (other measures than recycling used water)
Sediment quantity	
	Add/feed sediment (e.g. downstream from dam)
	Reduce undesired sediment input (e.g. from agricultural areas or from bank erosion other than riparian buffer strips!)
	Prevent sediment accumulation in reservoirs
	Improve continuity of sediment transport (e.g. manage dams for sediment flow)
	Trap sediments (e.g. building sediment traps to reduce wash load)
	Reduce impact of dredging
Flow dynamics	
	Establish environmental flows / naturalise flow regimes (does focus on discharge variability)
	Modify hydropeaking
	Increase flood frequency and duration in riparian zones or floodplains
	Reduce anthropogenic flow peaks
	Shorten the length of impounded reaches
	Favour morphogenic flows (could also be considered a measure to improve plan-form or in-channel habitat conditions
Longitudinal connectivity	
	Install fish pass, bypass, side channel for upstream migration
	Install facilities for downstream migration (including fish friendly turbines)
	Manage sluice, weir, and turbine operation for fish migration
	Remove barrier (e.g. dam or weir)
	Modify or remove culverts, syphons, piped streams
In-channel habitat conditions	
	Remove bed fixation
	Remove bank fixation
	Remove sediment (e.g. mud from groin fields)
	Add sediment (e.g. gravel)

Measure category	Measure
	Manage aquatic vegetation (e.g. mowing)
	Remove or modify in-channel hydraulic structures (e.g. groins, bridges)
	Creating shallows near the bank
	Recruitment or placement of large wood
	Boulder placement
	Initiate natural channel dynamics to promote natural regeneration
	Create artificial gravel bar or riffle
Riparian zone	
	Develop buffer strips to reduce nutrient input
	Develop buffer strips to reduce fine sediment input
	Develop natural vegetation on buffer strips (other reasons than nutrient or sediment input, e.g. shading, organic matter input)
River planform	
	Re-meander water course (actively changing planform)
	Widening or re-braiding of water course (actively changing planform)
	Shallow water course (actively increasing level of channel-bed)
	Narrow over-widened water course (actively changing width)
	Create low-flow channels in over-sized channels
	Allow/initiate lateral channel migration (e.g. by removing bank fixation and adding large wood)
	Create secondary floodplain on present low level of channel bed
Floodplain	
	Reconnect existing backwaters, oxbow-lakes, wetlands
	Create semi-natural / artificial backwaters, oxbow-lakes, wetlands
	Lowering embankments, levees or dikes to enlarge inundation and flooding
	Back-removal of embankments, levees or dikes to enlarge the active floodplain area
	Remove embankments, levees or dikes or other engineering structures that impede lateral connectivity
	Remove vegetation

2.6 Additional notes to the fact sheets

Boral river types

Petersen at al. 1995 divides the boreal rivers according to vegetation zones into 1) southern deciduous-forest rivers, 2) southern mixed coniferous forest rivers 3) boreal rivers and 4) alpine and arctic rivers. The southern deciduous-forest rivers include rivers in Denmark and the coastal area along southern and western Norway and southern parts of Sweden. The catchments have a low gradient and fertile soils and can be directly considered as “low energy, lowland rivers with fine to very fine bed sediment” and are not considered here for boreal perspective. Both group 2) southern mixed coniferous forest rivers and 3) boreal rivers can be considered to belong to “single-thread, mid-altitude boreal rivers”. By contrast, some of the alpine and arctic rivers are of glacial origin and some belong to “high energy, highland rivers”.

The main current anthropogenic pressures for the “small and Medium-Large single-thread, mid-altitude rivers” in the boreal zone are related to catchment land use, especially forestry and agriculture. Historically, the channels of the rivers in Finland and Sweden were intensively used for timber floating and most therefore were channelized during the 19th and 20th century. In Finland only few rivers not draining to the Baltic Sea remained unchannelized. The channelization included i.a. straightening and narrowing of streams and homogenization of river bed structure. After 1970s there have been extensive restoration programs to restore the channelized rivers to resemble more their original, natural state. So far in-stream restoration has been the major restoration aim for this river type. In the following the measures, problems and constraints related to the in-stream restoration of channelized boreal streams are discussed.

Fact sheet: Small, single-thread, lowland rivers

General description

Valley- and planform	The valley form varies from a no distinctive valley to a U-shaped valley and the channel planform from a straight/sinuous to a more meandering planform.
Hydrology	In the natural situation entrenchment is minimal and the floodplain is completely inundated during minor floods. Most rivers are permanent, although some may dry up periodically in summer (especially organic type rivers). The hydrograph is low-moderately dynamic.
Morphology	The erosion-sedimentation processes are only local. There is only passive meandering shaping a single-thread channel. The banks are irregular, mainly shaped by tree roots. The river bottom consists of a combination of mineral and biotic microhabitats ranging from silt, sand and gravel, to fine and coarse particulate organic matter (e.g. fallen leaves), mosses, local stands of vascular hydrophytes and course woody debris (logs, debris dams).
Chemistry	Depending on the geology pH can vary from 4.5 to 8. The water quality is meso-eutrophic, except for peat area fed rivers that are slightly acid. A distinction can be made between siliceous and calcareous rivers.
Riparian zone	The wide floodplain is dominated by deciduous swamp forest. The river channel is accompanied by mainly *Alnus* trees that more or less fully shade the river bed.

Photo: Small, single-thread, lowland river in the Netherlands.

Pressures

Major pressures

The prevailing hydromorphological pressure in small, single-thread, lowland rivers is channelization, in combination with flow alteration (resulting from impoundment and drainage of agricultural and urban land), and alteration of the riparian vegetation.

Score of pressure level imposed on small, single-thread, lowland rivers categorised according to pressure category and pressure, respectively (score in comparison to other pressures within this river type: No = no pressure/stress, L = low pressure/stress, M = moderate pressure/stress, H = high pressure/stress).

Pressure category	**Pressure**	**Score**
Point sources	Point sources	H
Diffuse sources	Diffuse sources	H
Water abstraction	Surface water abstraction	L
	Groundwater abstraction	M
Flow alteration	Discharge diversions and returns	L
	Interbasin flow transfer	No
	Hydrological regime modification including erosion due to increase in peak discharges	H
	Hydropeaking	No
	Flush flow	H
	Impoundment	H
Barriers/Connectivity	Artificial barriers upriver from the site	L
	Artificial barriers downriver from the site	M
Channelization	Channelization / cross section alteration (e.g. deepening) including erosion due to this	H
	Sedimentation	M
Bank degradation	Bank degradation	H
Habitat degradation	Alteration of riparian vegetation	H
	Alteration of in-channels habitat	M
Others	e.g. Maintenance	H
	e.g. Exotic species	L

Problems and constraints for river restoration

Impoundment results in a reduction of natural flow velocity, causing the deposition of transported sediments. Overall channelization and impoundment strongly lowers microhabitat and flow velocity variety. Clearing of riparian forests reduces the amount of course woody debris in the channel and lowers the amount of shade which results in higher temperatures and temperature dynamics. Incision of the river bed due to channelization and flow alteration reduced the hydrological connectivity between river and floodplain.

Depending on the catchment groundwater abstractions can also play an important role in river degradation. Groundwater abstractions may indirectly lower the discharge of rivers, thereby decreasing the flow velocity and water depth. Reductions in base flow can lead to a drop in water level resulting in rivers to become intermittent.

A decrease in flow velocity combined with a lack of shading from riparian zone often results in strong macrophyte growth In many cases maintenance consisting of removing of aquatic vegetation and/or dredging is performed to counteract these effects.

Apart from hydromorphological pressures lowland rivers often suffer from eutrophication/ organic pollution resulting from a high proportion of agricultural land use in the catchment. Although this strongly the depends on the region, e.g. in Sweden acidification is the most important pressure.

Measures

Common restoration practice

Most of the measures taken in small, single-thread, lowland rivers aim to restore the channel planform (56%), mostly remeandering, or some intermediate solution, like a two stage profile. More often these measures are combined with in-channel measures, like removal of bank fixation and/or adding local structures such as groynes. Probably this is because of the low cost of in-channel measures compared to changes in channel planform that needs adjacent land. Measures that deal with the whole floodplain are rare, but when taken always in combination combined with in river or channel planform measures. Restoration of the riparian zone is always combined with channel planform and in-channel measures. The width is often limited.

Score per measure category/measure of relevance, effect in-channel, effect on the floodplain and costs the measure in comparison to other measures within this river type (No = no relevance or effect, L = low relevance or effect, M = moderate relevance or effect, H = high relevance or effect of the measure) and indication a prioritisation of measures (L = low priority, M = moderate priority, H = high priority).

Measure category	**Measure**	**Relevance**	**Effect in-channel**	**Effect floodplain**	**Costs**	**Prioritisation**
Decrease pollution	Decrease point source pollution	M	M	M	H	M
	Decrease diffuse pollution input	H	H	H	H	H
Water flow quantity	Reduce surface water abstraction	L	L	L	L	L
	Improve water retention	H	M	H	H	H
	Reduce groundwater abstraction	L	L	M	M	L
	Improve water storage	H	M	H	H	H
	Increase minimum flow	H	H	M	H	H
	Water diversion and transfer	L	L	No	L	L
	Recycle used water	L	L	No	L	L
	Reduce water consumption	L	L	No	L	L
Sediment quantity	Add/feed sediment	M	M	L	M	M
	Reduce undesired sediment input	M	M	L	H	M
	Prevent sediment accumulation	No				
	Improve continuity of sediment transport	No				
	Trap sediments	No				
	Reduce impact of dredging	L	L	No	L	L
Flow dynamics	Establish natural environmental flows	H	M	H	H	H

Measure category	Measure	Relevance	Effect in-channel	Effect floodplain	Costs	Prioritisation
	Modify hydropeaking	No				
	Increase flood frequency and duration	M	M	H	H	H
	Reduce anthropogenic flow peaks	H	M	L	H	H
	Shorten the length of impounded reaches	L	L	No	L	L
	Favour morphogenic flows	M	M	L	M	M
Longitudinal connectivity	Install fish pass, bypass, side channels	L	L	No	M	L
	Install facilities for downriver migration	L	L	No	M	L
	Manage sluice, weir, and turbine operation	L	L	No	M	L
	Remove barrier	M	M	L	L	M
	Modify or remove culverts, syphons, piped rivers	L	L	No	M	L
In-channel habitat conditions	Remove bed fixation	M	M	L	L	L
	Remove bank fixation	M	M	L	L	L
	Remove sediment	L	L	No	M	L
	Add sediment (e.g. gravel)	L	L	No	M	L
	Manage aquatic vegetation	M	M	L	H	M
	Remove in-channel hydraulic structures	L	L	No	M	L
	Creating shallows near the bank	L	L	No	M	L
	Recruitment or placement of large wood	M	M	L	H	H
	Boulder placement	No				
	Initiate natural channel dynamics	H	H	M	L	H
	Create artificial gravel bar or riffle	L	L	No	M	L
Riparian zone	Develop buffer strips to reduce nutrients	H	H	H	M	H
	Develop buffer strips to reduce fine sediments	M	M	M	M	M
	Develop natural vegetation on buffer strips	H	H	H	M	H
River planform	Re-meander water course	M	M	M	H	M
	Widening or re-braiding of water course	L	L	L	H	L
	Create a shallow water course	H	H	H	M	H
	Narrow over-widened water course	H	H	H	M	H
	Create low-flow channels	M	M	L	H	M
	Allow/initiate lateral channel migration	M	M	L	L	M
	Create secondary floodplain	M	M	M	H	M
Floodplain	Reconnect backwaters, oxbow-lakes, wet-	M	L	M	L	M

Measure category	Measure	Relevance	Effect in-channel	Effect floodplain	Costs	Prioritisation
	lands					
	Create backwaters, oxbow-lakes, wetlands	M	L	M	M	M
	Lower embankments, levees or dikes	M	L	M	L	M
	Replace embankments, levees or dikes	M	L	M	H	M
	Remove embankments, levees or dikes	M	L	M	L	M
	Remove vegetation	M	L	H	L	L

Problems and constraints with common restoration practice

The most often applied measure in lowland rivers is remeandering. In theory, remeandering will affect in-channel habitat conditions. However, in small, single-thread, sand-bed, lowland rivers there is limited potential for substrate sorting. Research showed that active remeandering of lowland rives can also decrease microhabitat diversity, i.e, there were cases where remeandering led to a decrease in river velocity resulting in particulate organic material as the main microhabitat, while in the unrestored section more habitats were present.

Hydrological measures are more often only locally applied in river stretches without solving the hydrological dynamics that results from catchment wide activities, like drainage, water abstraction and paved surfaces.

Promising and new measures

Restoring natural processes in long reaches, such as removal of bed and bank fixation, re-profiling and free flow, has a higher effect on recovery compared to local scale interventions, such as wood or gravel addition. Especially, in small, single-thread, lowland rivers catchment wide measures and measures restoring the natural system conditions (processes that fit to the current climatological and geo-morphological conditions) are most effective (see table below).

Hydrology must be considered as the most important process of which effects reach over the whole floodplain. Hydrological measures should therefore focus on groundwater balances and flows at catchment level. Upscaling of many current hydrological measures to reduce discharge dynamics and increase water- and groundwater levels is a promising trend (see figure below).

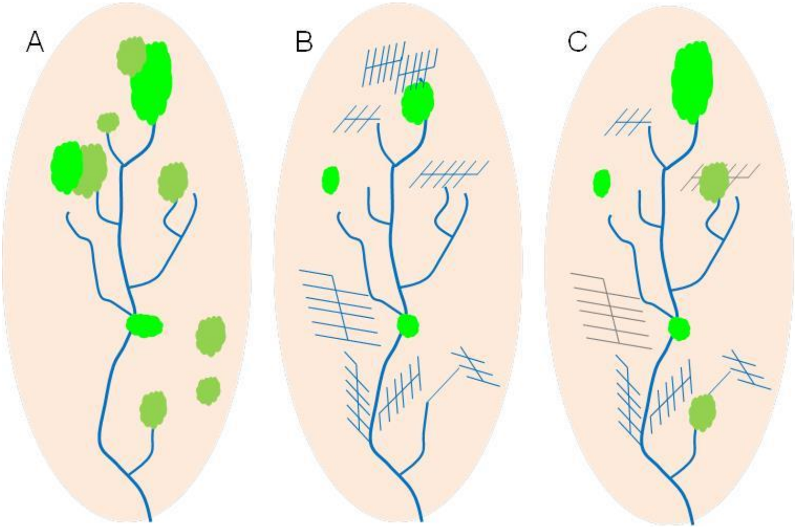

Figure: Hydrological restoration of combined ground water and surface water flows by restoring infiltration capacity and recreating water storage areas. (A: Natural catchment, B: Present situation with a high drainage intensity, C: Restored catchment with water infiltration, reduced drianage intensity, water storage areas (green) and water flow re-tarding by remeandering).

Especially, at the scale of the catchment and floodplain such measures will sort strong effects. The river is not considered in solitude but is seen and dealt with as part of its catchment and floodplain.

Furthermore, free flow and thus connectivity provides continuous potential of exchange of water, substances and propagules. Also tackling nutrient, organic and toxic load will sort most effect when tackled at catchment level. Here obligatory guidelines are needed.

But nutrients, organic and toxic substances and sediments can also be reduced at river stretch level by introducing wider or smaller riparian buffers (see figure below). There is clear and, in many cases, strong evidence for the role of wooded riparian buffers in con-trolling nutrient and sediment retention, water temperature and improving in-channel habitat structure.

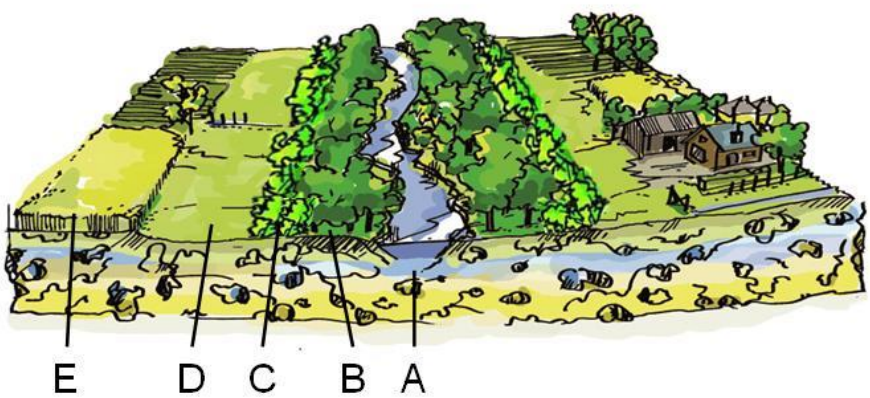

Figure: Installing extended buffer zones will control nutrient and sediment run off, cool water temperature and improve in-channel habitat structure. (A: river, B: Tree-zone, C: Bush-zone, D: grass-zone, E: adjacent land).

At river stretch scale also profile adaptations are in benefit. As the stream power of this river type is low active measures for re-profiling are considered beneficial. Also changing maintenance from a negative to a positive measure by lowering the maintenance frequency and diversifying the frequency and intensity depending on local plant growth and flow conditions, improves the river stretch.

At local scale morphological processes (e.g. sorting of bed material, creation of pools, bars and cut-banks) are generally the result of high flows in rich structured beds. By addition of wood or gravel habitat morphology can be improved. Monitoring results indicated that channel incision could alternatively be decreased or even reversed by placing a large number of naturally shaped logs randomly in the river. Logs in combination with sand addition to the river will heighten the river bed, increase the flow and flow variability and improve habitat heterogeneity.

Table: Promising measures and respective scale. The higher the scale the more effective the measure.

	Ecological key factor				
Scale	Temperature and light regime (System conditions)	Flow regime (Hydrology)	Profile variation, substrate heterogeneity and organic material (Morphology)	Oxygen regime, nutrient and toxic load (Chemistry)	Connectivity (Biology)
Catchment	Ground water				
	Surface water hydrology				
		Free flow ↔		Connectivity	
			Nutrients and organic load		
				Toxicants	
River stretch	Riparian zone				
		Profile			
		Maintenance			
Site		Habitat			

In conclusion, one can hierarchically order in nine steps the measures to restore small, single-thread, lowland rivers keeping both stress and key ecological processes into account:

		Ecological key factors/ processes										
	Stressors	**Order of restoration**	***Temperature*** *regime*	***Light*** *regime*	***Flow*** *regime*	***Substrate*** *variation*	***Organic matter***	***Oxygen*** *regime*	***Nutrients***	***Salinity***	***Toxicity***	***Connectivity***
Catchment	Changed hydrology	1	■		■	■						
	Diffuse sources	2		■	■	■	■	■	■	■	■	
	Point sources	3	■	■	■	■	■	■	■	■	■	
Stretch	Current alterations	4	■		■	■		■				
	Channelization	5	■	■	■	■	■	■				■
	Bank degradation	6	■	■	■	■	■	■	■			■
	Maintenance	7		■	■	■	■	■				
Site	Barriers	8	■		■	■		■				■
	Habitat degradation	9	■		■	■	■					

Monitoring scheme

Monitoring schemes should follow some basic principles that apply to all river types:

- Biotic as well as abiotic variables should be monitored. The restoration measures might have succeeded to create the desired habitats but the effect on biota might be limited due to other pressures at larger scales which have not been addressed in the restoration project.
- In-channel, riparian, as well as floodplain conditions should be monitored. Besides the biological quality elements relevant for the Water Framework Directive, restoration can also have positive effects on other semi-aquatic and terrestrial organism groups, like ground beetles and floodplain vegetation. Indeed, there is empirical evidence that effects on other organism groups can be larger.
- Monitoring has to be conducted at appropriate spatial and temporal scales that reflect (i) the habitat needs of the organisms (e.g. monitoring microhabitat substrate patches for macroinvertebrates, mesohabitat features for fish), (ii) all life stages (e.g. monitoring in-channel and riparian habitats for macroinvertebrates with terrestrial life-stages), (iii) and the reproductive cycle as well as dispersal abilities (long-term monitoring to also cover effects of restoration on long-lived species and weak dispersers).
- Looking at the spatial and time scale of many current restoration measures macro-invertebrates are most suited for river monitoring. Fish population are strongly managed and reflect larger scale conditions, macrophytes bear a long history as they disappear only slowly and algae reflect to short time scales and very, very local conditions. Floodplains are large scaled and best be monitored by vegetation. Riparian zone can be monitored by using vegetation or carabid beetles.
- A Before-After-Control-Impact design should be applied to allow disentangling the effect of restoration from general trends in the whole river or catchment.

- However, the final selection of the organism groups, and spatial / temporal scales monitored strongly depends on the objectives and applied measures. Of course, it is reasonable to focus on the abiotic and biotic variables and scales that potentially have been affected by the restoration measures (e.g. in-channel habitat conditions by in-channel measures).
- Monitoring results should be used for adaptive management, i.e. to react on unanticipated effects and trends, and this should be included in the planning from the beginning ("Plan-B").

For further reading and practical guidelines we refer to the handbook of the River Restoration Centre (River Restoration Centre 2011).

The relevance of a variable at the scale of the river, riparian zone and floodplain scored in comparison to other variables within this river type (No = no relevance, L = low relevance, M = moderate relevance, H = high relevance)

Variable group	**Variable**	**River**	**Riparian zone**	**Floodplain**
River hydrology		H	H	H
In-channel hydraulics		H	M	L
Floodplain morphology		L	L	M
In-channel morphology	Profile (longitudinal, transversal)	H	M	M
	Meso-/micro-structures	H	L	No
Chemistry	Nutrients	H	M	L
	Toxicants	H	M	L
	Others			
Biology	Algae	L	No	No
	Macrophytes	M	L	No
	Macroinvertebrates	H	L	No
	Fish	H	L	No
	Floodplain/riparian vegetation	L	H	H
	Terrestrial fauna	No	H	M

Fact sheet: Medium-large, single-thread, lowland rivers

General description

Valley- and planform	The valley form varies from a no distinctive valley to a U-shaped valley and the channel planform from a straight/sinuous to a more meandering planform.
Hydrology	In the natural situation entrenchment is minimal and the floodplain is partly to completely inundated during floods. Large, single-thread, lowland rivers are permanent. The hydrograph is moderately dynamic. In-channel mesohabitats create a large variety in current velocities and depths.
Morphology	The erosion-sedimentation processes are occur in channel and along the river margins. There is only passive meandering shaping a single-thread channel. The banks are irregular, mainly shaped by tree roots or in wet places by reed, rushes or sedges vegetation. The river bottom consists of a combination of mineral and organic microhabitats ranging from silt, sand and gravel, to fine and coarse particulate organic matter (e.g. fallen leaves), mosses, local stands of vascular hydrophytes and course woody debris (logs, debris dams). Macrophytes can take parts of the channel.
Chemistry	Depending on the geology pH can vary from 6 to 8. The water quality is meso-eutrophic, except for peat area fed rivers that are slightly acid. A distinction can be made between siliceous and calcareous rivers. Primary productivity takes place
Riparian zone	The wide floodplain is either dominated by deciduous swamp forest or consists out of higher and drier areas dependent on the geomorphology of the valley. The river channel is accompanied by mainly *Alnus*, *Fraxinus*, and *Salix* trees that only partly shade the river bed.

Photo: Large, single-thread, lowland river Dinkel in the Netherlands.

Pressures

Major pressures

The prevailing hydromorphological pressure in large, single-thread, lowland rivers is channelization, in combination with flow alteration (resulting from impoundment and drainage of agricultural and urban land), and alteration of the riparian vegetation and the floodplain water infrastructure.

Score of pressure level imposed on large, single-thread, lowland rivers categorised according to pressure category and pressure, respectively (score in comparison to other pressures within this river type: No = no pressure/stress, L = low pressure/stress, M = moderate pressure/stress, H = high pressure/stress).

Pressure category	Pressure	Score
Point sources	Point sources	H
Diffuse sources	Diffuse sources	H
Water abstraction	Surface water abstraction	L
	Groundwater abstraction	L
Flow alteration	Discharge diversions and returns	M
	Interbasin flow transfer	L
	Hydrological regime modification including erosion due to increase in peak discharges	H
	Hydropeaking	No
	Flush flow	H
	Impoundment	H
Barriers/Connectivity	Artificial barriers upriver from the site	M
	Artificial barriers downriver from the site	H
Channelization	Channelisation / cross section alteration (e.g. deepening) including erosion due to this	H
	Sedimentation	L
Bank degradation	Bank degradation	H
Habitat degradation	Alteration of riparian vegetation	L
	Alteration of in-channels habitat	H
Others	e.g. Maintenance	L
	e.g. Exotic species	H

Problems and constraints for river restoration

Impoundment results in a reduction of natural flow velocity, causing the deposition of transported sediments, especially silt. Overall channelization and impoundment strongly lowers microhabitat and flow velocity variety. Clearing of riparian forests reduces the amount of course woody debris in the channel and lowers the amount of shade which results in higher temperatures and temperature dynamics. Incision of the river bed due to channelization and flow alteration reduced the hydrological connectivity between river and floodplain.

Depending on the catchment groundwater lowering plays an important role in river degradation due to increase of peak flows and decrease of low flows, sometimes to stagnation. Surface water abstractions may indirectly lower the discharge of rivers, thereby decreasing the flow velocity, especially in dry periods. Reductions in base flow can lead to a drop in water level, stagnation with high temperatures and low oxygen levels.

The decrease in flow velocity often results in strong macrophyte growth. Deeper river parts become siltated. In many cases maintenance consisting of removing of aquatic vegetation and/or dredging is performed to counteract these effects.

Apart from hydromorphological pressures lowland rivers often suffer from eutrophication/ organic pollution resulting from a high proportion of agricultural land use in the catchment.

Measures

Common restoration practice

Most of the measures taken in large, single-thread, lowland rivers aim to reconnect old river meanders, remove weirs and restore river banks. Sometimes these measures are combined with in-channel measures, like removal of bank fixation and/or adding local structures such as tree logs. Probably this is because of the low cost of in-channel measures compared to changes in channel planform that needs adjacent land. Measures that deal with the upstream part of the river or the whole floodplain are rare. Restoration of the riparian zone is always limited to local areas where rewetting is a possibility. Often water safety arguments support rewetting areas or creating inundation – water storage areas.

Score per measure category/measure of relevance, effect in-channel, effect on the floodplain and costs the measure in comparison to other measures within this river type (No = no relevance or effect, L = low relevance or effect, M = moderate relevance or effect, H = high relevance or effect of the measure) and indication a prioritisation of measures (L = low priority, M = moderate priority, H = high priority).

Measure category	**Measure**	**Relevance**	**Effect in-channel**	**Effect floodplain**	**Costs**	**Prioritisation**
Decrease pollution	Decrease point source pollution	M	M	M	H	M
	Decrease diffuse pollution input	H	H	H	H	H
Water flow quantity	Reduce surface water abstraction	L	L	M	M	L
	Improve water retention	H	H	H	H	H
	Reduce groundwater abstraction	M	M	M	M	M
	Improve water storage	H	H	H	M	H
	Increase minimum flow	H	H	M	H	H
	Water diversion and transfer	M	M	M	H	M
	Recycle used water	L	L	No	L	L
	Reduce water consumption	L	L	No	L	L

Measure category	Measure	Relevance	Effect in-channel	Effect floodplain	Costs	Prioritisation
Sediment quantity	Add/feed sediment	H	H	M	M	M
	Reduce undesired sediment input	M	M	L	H	M
	Prevent sediment accumulation	No				
	Improve continuity of sediment transport	M	M	L	M	M
	Trap sediments	No				
	Reduce impact of dredging	M	M	L	M	M
Flow dynamics	Establish natural environmental flows	H	H	H	H	H
	Modify hydropeaking	No				
	Increase flood frequency and duration	H	H	H	H	H
	Reduce anthropogenic flow peaks	H	H	M	H	H
	Shorten the length of impounded reaches	H	H	M	H	H
	Favour morphogenic flows	H	H	M	H	H
Longitudinal connectivity	Install fish pass, bypass, side channels	H	H	L	M	M
	Install facilities for downriver migration	H	H	L	M	M
	Manage sluice, weir, and turbine operation	M	M	L	M	M
	Remove barrier	H	H	L	M	M
	Modify or remove culverts, syphons, piped rivers	No				
In-channel habitat conditions	Remove bed fixation	No				
	Remove bank fixation	H	H	M	M	M
	Remove sediment	No				
	Add sediment (e.g. gravel)	L	L	No	M	L
	Manage aquatic vegetation	H	H	M	H	H
	Remove in-channel hydraulic structures	M	H	L	M	M
	Creating shallows near the bank	M	H	L	M	M
	Recruitment or placement of large wood	H	H	M	L	H
	Boulder placement	No				
	Initiate natural channel dynamics	H	H	M	L	H
	Create artificial gravel bar or riffle	L	L	No	M	L
Riparian zone	Develop buffer strips to reduce nutrients	M	M	M	M	M
	Develop buffer strips to reduce fine sediments	M	M	M	M	M
	Develop natural vegetation on buffer strips	H	H	H	M	H
River planform	Re-meander water course	M	M	M	H	M

Measure category	Measure	Relevance	Effect in-channel	Effect floodplain	Costs	Prioritisation
	Widening or re-braiding of water course	M	M	H	H	M
	Create a shallow water course	H	H	H	M	H
	Narrow over-widened water course	H	H	H	M	H
	Create low-flow channels	M	M	L	H	M
	Allow/initiate lateral channel migration	H	H	M	M	H
	Create secondary floodplain	H	M	H	H	H
Floodplain	Reconnect backwaters, oxbow-lakes, wet-lands	M	L	M	L	M
	Create backwaters, oxbow-lakes, wetlands	M	L	M	M	M
	Lower embankments, levees or dikes	H	M	H	L	M
	Replace embankments, levees or dikes	M	L	M	H	M
	Remove embankments, levees or dikes	H	M	H	L	M
	Remove vegetation	No				

Problems and constraints with common restoration practice

The most often applied measure in lowland rivers is reconnecting old meanders and ox-bow lakes. Sometimes former secondary channels are reconnected or are newly dug. In large, single-thread, sand-bed, lowland rivers there is limited potential for substrate sorting, except when the river bed is heightened and made wider.

Hydrological measures are more often only limited applied without solving the hydrological dynamics that results from catchment wide activities, like drainage, water abstraction and paved surfaces.
Morphological measures often most common and are easy to take, like removal of bank fixation or placement of inchannel habitat structures. Such measures favor engineered solutions that create more static habitats of which it remains a question whether they sustain under the current hydromorphological regime.

Measures that tackle chemical substances are often limited to point sources. Large parts of the chemical load though enter the river system as diffuse inflow.

Promising and new measures

Four basic principles in future process-based restoration must be kept in mind:

1. Target the root causes of lowland river ecosystem change and do this at different scales.

Restoration actions that target root causes of degradation rely on knowledge of 1) the processes that drive river ecosystem conditions, and 2) effects of human induced alterations onto those driving processes. Restoration of natural processes fitting the natural geo-hydrological, -morphological, and –chemical conditions will sort highest success.

2. Tailor restoration measures to the river ecosystems' potential, starting at the large scale and follow the hierarchical pathway to the local scale.

Each river ecosystem is part of a large catchment and the river itself depends strongly on the range of channel and riparian conditions. Both catchment and riparian valley should be or become the logical outcome of the physiographic and climatic setting. Furthermore, understanding the processes controlling restoration outcomes helps to design restoration measures that redirect river valley, river channel and river habitat conditions.

3. Match the scale of restoration to the scale of the problem.

When disrupted processes causing degradation are at the reach scale (e.g., channel modification, levees, removal of riparian vegetation), restoration actions at individual reaches can effectively address root causes. When causes of degradation are at the catchment scale (e.g., increased runoff due to impervious surfaces, increased eutrophication), restoration actions can only be taken at catchment level to restore the root causes.

4. Be explicit about expected outcomes.

Process-based restoration is a long-term endeavor, and there are often long lag times between implementation and recovery. Ecosystem features will also continuously change through natural dynamics, and biota may not improve dramatically with any single individual action. Hence, quantifying the restoration outcome is critical to setting appropriate expectations for river restoration.

Process oriented restoration focuses on restoring critical drivers and river functions. Process oriented actions will help to avoid common pitfalls of engineered solutions, such as the creation of habitats that are beyond a river stretch's natural potential. Restoring natural processes in long reaches, such as giving freedom to erosion-sedimentation processes by removal of bed and bank fixation, re-profiling and free flow has a higher effect on recovery compared to local scale interventions, such as wood addition. Especially, in large, single-thread, lowland rivers catchment wide measures and measures restoring the natural system conditions (processes that fit to the current climatological and geomorphological conditions) are most effective (table 3).

Hydrology must be considered as the most important driving process of which effects reach over the whole floodplain. Hydrological measures should therefore focus 1) on groundwater balances and flows at catchment level and 2) on catchment wide hydrological surface water infrastructure and its functioning. Upscaling of many current hydrological measures to reduce discharge dynamics and increase water- and groundwater levels is a promising trend (figure 1).

Table: Promising measures and respective scale. The higher the scale the more effective the measure.

	Ecological key factor				
Schaal	Temperature and light regime (System conditions)	Flow regime (Hydrology)	Profile variation, substrate heterogeneity and organic material (Morphology)	Oxygen regime, nutrient and toxic load (Chemistry)	Connectivity (Biology)
Catchment	Ground water				
	Surface water hydrology				
		Free flow	↔	Connectivity	
				Nutrients and organic load	
				Toxicants	
River stretch	Riparian zone				
		Profile			
		Maintenance			
Site		Habitat			

Especially, at the scale of the catchment and floodplain such measures will sort strong effects. The river is not considered in solitude but is seen and dealt with as part of its catchment and floodplain.

Furthermore, free flow and thus connectivity provides continuous potential of exchange of water, substances and propagules. For example, natural levees develop by spill-over of sediment during periods of high flow. Parallel to the channel mostly sand is deposited at the highest flow velocities, and sand compacts less than the mud that is deposited farther away onto the floodplain. Over time the near-channel sand deposits will rise above the more spread and compacted floodplain and form natural levees. A meandering river migrates laterally by sediment erosion on the outside of the meander bend, as that is the part with erosion, and deposition on the inside. The processes of helicoidal flow, deceleration, channel lag, point bar sequence, and fining upwards shape the longitudinal profile. Parallel to the channel bank levee deposits build up, and gradually raise up the river over the floodplain which is covered by more fine sediments. In a more humid climate the floodplain area beyond the levees may be covered with water longer periods of time and may form a swamp (backswamp). Meanders cut into each other as they grow (neck cutoffs), and then the river shortcuts. So, growing meanders reduce the slope and cutoffs increase the slope again (a feedback loop). When the old meander is abandoned anoxbow lakes is formed. This lake slowly fills with fine sediment during floods and with organic material due to macrophyte production. As a river builds up its levees and raises itself over the floodplain, the slope and the transport power of the stream decrease, the channel fills gradually with sediment, and finally (often during a flood) the river will breach its levee and avulsion in a new channel that follows a steeper path down the valley will occur.

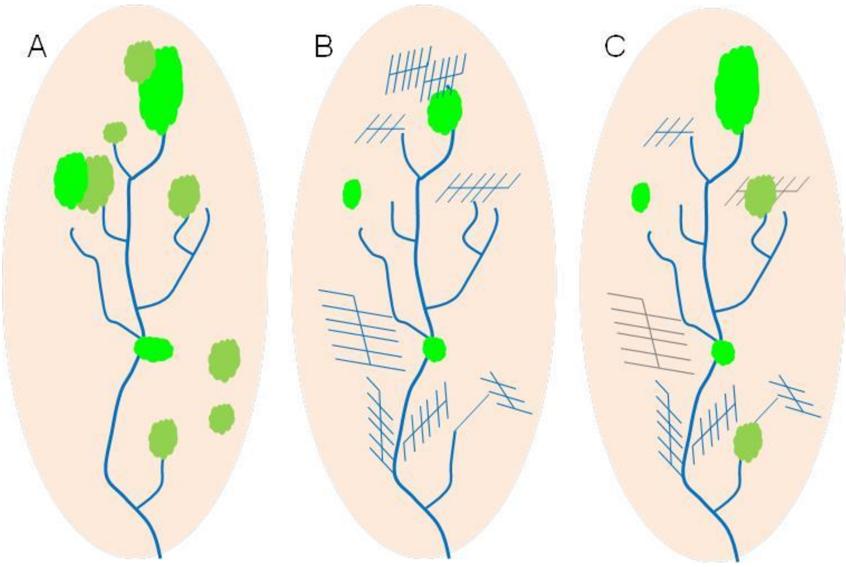

Figure: Process oriented hydrological restoration of combined ground water and surface water flows by restoring infiltration capacity and recreating water storage areas. (A: Natural catchment, B: Present situation; with a high drainage intensity, C: Restored catchment with water infiltration, reduced drainage intensity, water storage areas (green) and water flow retarding by remeandering).

Also tackling nutrient, organic and toxic load by legislation and control will sort most effect when tackled at catchment level. Here obligatory guidelines are needed.

But nutrients, organic and toxic substances and sediments can also be reduced at river stretch level by introducing wider riparian buffers (Figure 3). There is clear and, in many cases, strong evidence for the role of wooded riparian buffers in controlling nutrient and sediment retention and improving in-channel habitat structure. For large rivers these measures should also be implemented at many (>50%) of the upstream channels in the catchment.

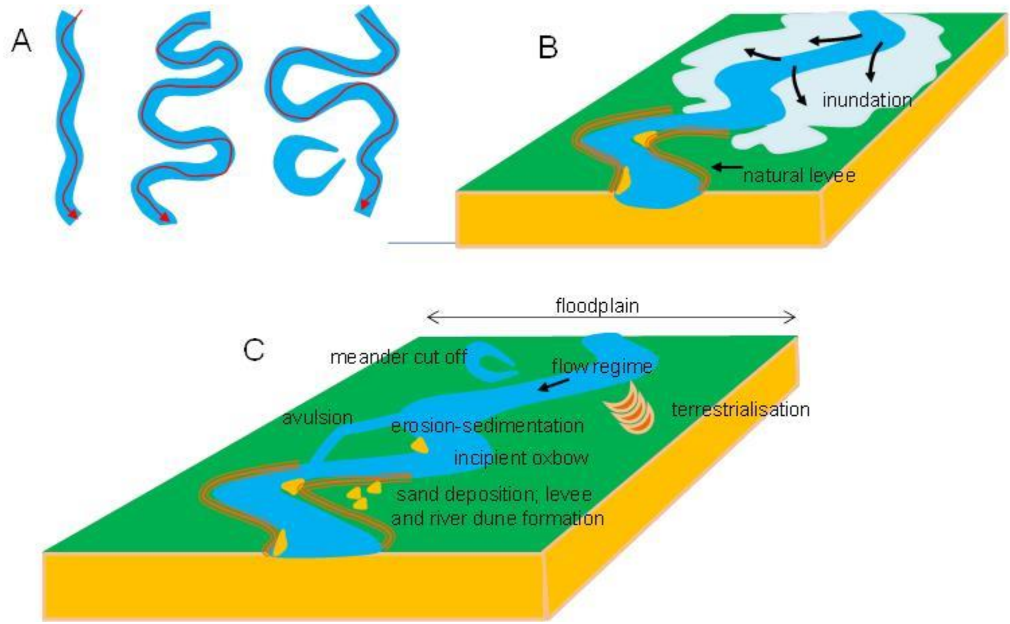

Figure: Process oriented hydromorphological restoration by providing space for free meander processes (A: meanders grow laterally through erosion of the outside bend and sedimentation at the inside bend, often through a point bar. When the channel bend gets too large and consumes too much energy, the river will eventually form a less energetically shortcut, and a part of the old channel will be abandoned and becomes an oxbow lake.), inundation by a shallow river depth and a high water level so avulsions and natural levee development occur (B), and in-channel erosion-sedimentation and in the floodplain, oxbow terrestrialisation and other processes give room for valley formation processes (C).

At river stretch scale also profile adaptations (both making the bed more shallow and, if necessary for safety reasons wider) are in benefit. As the stream power of this river type is low active measures for re-profiling (shallower, wider, profile diversity) are considered beneficial. Also changing maintenance from a negative to a positive measure by lowering the maintenance frequency and diversifying the frequency and intensity depending on local plant growth and flow conditions, improves the river stretch.

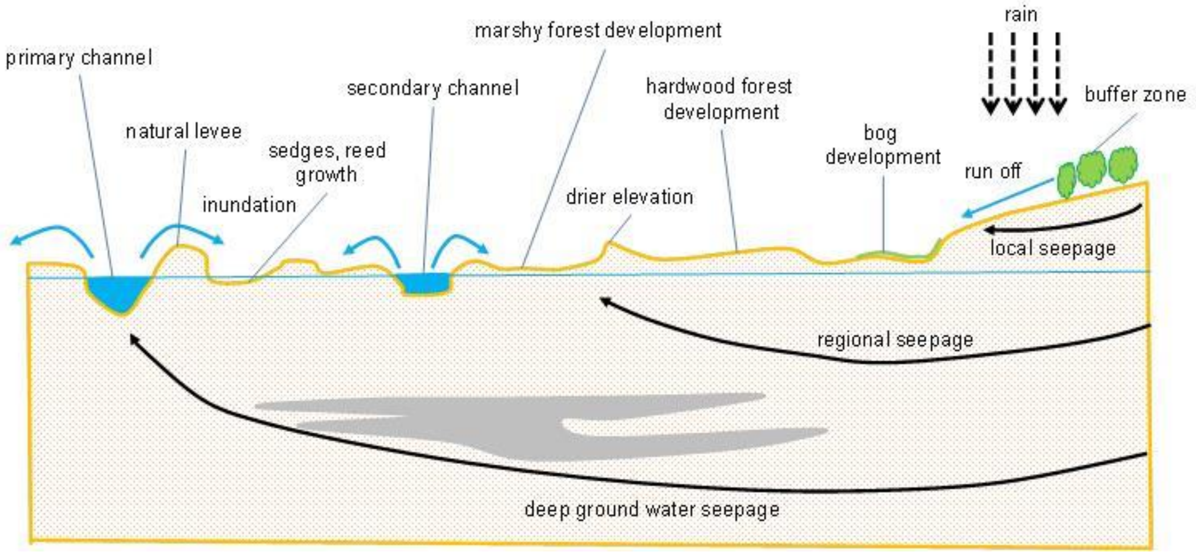

Figure: Stretch scale processes for river floodplain development with natural ground water, rain water and surface water flows that provide the basis for morphological processes. Buffer zone and measures to reduce nutrient levels provide the basis for lowland river restoration.

At local scale morphological processes (e.g. sorting of bed material, creation of pools, bars and cut-banks) are generally the result of high flows in rich structured beds. Best is to restore those processes that create local habitat and substrate variety. By addition of wood or gravel habitat morphology can be improved. Placing logs into the river will structure the river bed, increase the flow variability and improve habitat heterogeneity.

Monitoring scheme

Monitoring schemes should follow some basic principles that apply to all river types:

- Biotic as well as abiotic variables should be monitored. The restoration measures might have succeeded to create the desired habitats but the effect on biota might be limited due to other pressures at larger scales which have not been addressed in the restoration project.
- In-channel, riparian, as well as floodplain conditions should be monitored. Besides the biological quality elements relevant for the Water Framework Directive, restoration can also have positive effects on other semi-aquatic and terrestrial organism groups, like ground beetles and floodplain vegetation. Indeed, there is empirical evidence that effects on other organism groups can be larger.
- Monitoring has to be conducted at appropriate spatial and temporal scales that reflect (i) the habitat needs of the organisms (e.g. monitoring microhabitat substrate patches for macroinvertebrates, mesohabitat features for fish), (ii) all life stages (e.g. monitoring in-channel and riparian habitats for macroinvertebrates with terrestrial life-stages), (iii) and the reproductive cycle as well as dispersal abilities (long-term monitoring to also cover effects of restoration on long-lived species and weak dispersers).
- Looking at the spatial and time scale of many current restoration measures macro-invertebrates are most suited for river monitoring. Fish population are strongly managed and reflect larger scale conditions, macrophytes bear a long history as they disappear only slowly and algae reflect to short time scales and very, very local conditions. Floodplains are large scaled and best be monitored by vegetation. Riparian zone can be monitored by using vegetation or carabid beetles.
- A Before-After-Control-Impact design should be applied to allow disentangling the effect of restoration from general trends in the whole river or catchment.
- However, the final selection of the organism groups, and spatial / temporal scales monitored strongly depends on the objectives and applied measures. Of course, it is reasonable to focus on the abiotic and biotic variables and scales that potentially have been affected by the restoration measures (e.g. in-channel habitat conditions by in-channel measures).
- Monitoring results should be used for adaptive management, i.e. to react on unanticipated effects and trends, and this should be included in the planning from the beginning ("Plan-B").

For further reading and practical guidelines we refer to the handbook of the River Restoration Centre (River Restoration Centre 2011).

The relevance of a variable at the scale of the river, riparian zone and floodplain scored in comparison to other variables within this river type (No = no relevance, L = low relevance, M = moderate relevance, H = high relevance)

Variable group	**Variable**	**River**	**Wetland zone**	**Floodplain**
River hydrology		H	H	H
In-channel hydraulics		H	L	L
Floodplain morphology		L	M	H
In-channel morphology	Profile (longitudinal, transversal)	H	M	L
	Meso-/micro-structures	H	M	L
Chemistry	Nutrients	H	H	L
	Toxicants	H	M	L
	Others			
Biology	Algae	L	L	No
	Macrophytes	H	H	L
	Macroinvertebrates	H	H	M
	Fish	H	M	M
	Floodplain/riparian vegetation	L	H	H
	Terrestrial fauna	No	H	M

Fact sheet: Small, anastomosing, lowland rivers

General description

Valley- and planform	The valley form varies from a no distinctive valley to a wide U-shaped valley and the channel planform consists of a multiple channel river characterized by vegetated or otherwise stable alluvial islands that divide flows. Each channel in itself can have a straight/sinuous to a more meandering planform.
Hydrology	In the natural situation entrenchment of the channels is minimal and the floodplain is completely inundated during floods. Anastomosing, lowland rivers can be permanent or some channels maybe intermittent. The hydrograph is (moderately) dynamic.
Morphology	The channels are laterally stable due to stabilizing vegetation in combination with relatively low stream power. The erosion-sedimentation processes are only local. Channel formation is slow due to channel sedimentation, the formation of vegetation or ineffective flow due to the very low channel gradient. The channel banks are irregular, mainly shaped by tree roots. The river bottom is dominated by mineral and organic silt, and fine and coarse particulate organic matter (e.g. fallen leaves), mosses, local stands of vascular hydrophytes and course woody debris (logs, debris dams).
Chemistry	Depending on the age and channel slope the floodplain has become organic (peat formation) and the pH can vary from 4.5 to 7. The water quality is mesotrophic.
Riparian zone	The floodplain is dominated by deciduous swamp forest. The river channels are accompanied by mainly *Alnus* trees that more or less fully shade the river beds.

Photo: Small, anastomosing, lowland river in Poland.

Pressures

Major pressures

The prevailing hydromorphological pressure in small, anastomosing, lowland rivers is drainage of the floodplain and channelization, in combination with flow alteration (resulting from impoundment and drainage of agricultural and urban lands elsewhere in the catchment), and alteration of the riparian and floodplain vegetation.

Score of pressure level imposed on small, anastomosing, lowland rivers categorised according to pressure category and pressure, respectively (score in comparison to other pressures within this river type: No = no pressure/stress, L = low pressure/stress, M = moderate pressure/stress, H = high pressure/stress).

Pressure category	**Pressure**	**Score**
Point sources	Point sources	H
Diffuse sources	Diffuse sources	H
Water abstraction	Surface water abstraction	M
	Groundwater abstraction	H
Flow alteration	Discharge diversions and returns	L
	Interbasin flow transfer	No
	Hydrological regime modification including erosion due to increase in peak discharges	H
	Hydropeaking	No
	Flush flow	M
	Impoundment	H
Barriers/Connectivity	Artificial barriers upriver from the site	M
	Artificial barriers downriver from the site	M
Channelization	Channelisation / cross section alteration (e.g. deepening) including erosion due to this	H
	Sedimentation	M
Bank degradation	Bank degradation	H
Habitat degradation	Alteration of riparian vegetation	H
	Alteration of in-rivers habitat	L
Others	Maintenance	H
	Exotic species	L

Problems and constraints for river restoration

Floodplain drainage and channelization strongly lower the ground and surface water levels. Side channels will become intermittent or will dry up. Due to downstream channelization the main channel will incise with further water level lowering and drying up of the floodplain. More dynamic flows will scour the river bed and change it to a more mineral system.

Clearing of riparian forests reduces the bank stability and the amount of course woody debris in the channels and lowers the amount of shade which results in higher temperatures and temperature dynamics, more macrophyte growth and potential bank erosion. Incision of the main channel bed due to channelization and flow alteration will strongly reduce the hydrological connectivity between river and floodplain.

Depending on the catchment (ground)water abstractions can also play an important role in river flow alteration. Groundwater abstractions may lower the discharge of rivers, thereby decreasing the flow velocity and water depth with further terrestrialisation of smaller channels.

In many cases maintenance consisting of removing of aquatic vegetation and/or dredging is performed to counteract effects of macrophyte development and channel obstruction.

Apart from hydromorphological pressures these lowland rivers often suffer from eutrophication and organic pollution resulting from a high proportion of agricultural land use upstream in the catchment.

Measures

Common restoration practice

There is little literature available on measures taken to restore small, anastomosing, lowland rivers. Probably this is because of the high costs of floodplain wide measures that include either buying of land or changing land use due to a strong raise in ground water level. Thus, measures that deal with the whole floodplain are rare, but when taken always in combination combined with in river or channel planform measures. The length of a restored stretch is mostly limited to a lower part of the valley. In ideal cases the processes that result in multiple channels are restored. Active multiple channel initiation lacks.

Score per measure category/measure of relevance, effect in-river, effect on the floodplain and costs the measure in comparison to other measures within this river type (No = no relevance or effect, L = low relevance or effect, M = moderate relevance or effect, H = high relevance or effect of the measure) and indication a prioritisation of measures (L = low priority, M = moderate priority, H = high priority).

Measure category	Measure	Relevance	Effect in-channel	Effect floodplain	Costs	Prioritisation
Decrease pollution	Decrease point source pollution	L	L	M	H	L
	Decrease diffuse pollution input	H	M	H	H	H
Water flow quantity	Reduce surface water abstraction	H	M	H	L	H
	Improve water retention	H	M	H	H	H
	Reduce groundwater abstraction	H	M	H	M	H
	Improve water storage	H	M	H	H	H
	Increase minimum flow	H	H	H	H	H
	Water diversion and transfer	M	M	M	H	M
	Recycle used water	H	M	H	H	H

Measure category	Measure	Relevance	Effect in-channel	Effect floodplain	Costs	Prioritisation
	Reduce water consumption	H	M	H	H	H
Sediment quantity	Add/feed sediment	L	M	L	M	L
	Reduce undesired sediment input	L	M	L	M	L
	Prevent sediment accumulation	L	L	M	M	L
	Improve continuity of sediment transport	M	M	M	M	M
	Trap sediments	L	M	L	M	L
	Reduce impact of dredging	H	M	H	M	H
Flow dynamics	Establish natural environmental flows	H	H	H	H	H
	Modify hydropeaking	No				
	Increase flood frequency and duration	H	M	H	H	H
	Reduce anthropogenic flow peaks	H	M	H	H	H
	Shorten the length of impounded reaches	L	L	No	L	L
	Favour morphogenic flows	M	M	M	M	M
Longitudinal connectivity	Install fish pass, bypass, side channels*	H*	M*	H*	L*	H*
	Install facilities for downriver migration	No				
	Manage sluice, weir, and turbine operation	No				
	Remove barrier	H	H	H	M	H
	Modify or remove culverts, syphons, piped rivers	H	H	H	M	H
In-channel habitat conditions	Remove bed fixation	H	H	H	M	H
	Remove bank fixation	H	H	H	M	H
	Remove sediment	L	L	L	M	L
	Add sediment (e.g. gravel)	L	L	L	M	L
	Manage aquatic vegetation	M	M	M	H	M
	Remove in-channel hydraulic structures	H	H	H	M	H
	Creating shallows near the bank	L	L	L	M	L
	Recruitment or placement of large wood	M	M	L	H	H
	Boulder placement	No				
	Initiate natural channel dynamics	H	H	M	L	H
	Create artificial gravel bar or riffle	L	L	No	M	L
Riparian zone	Develop buffer strips to reduce nutrients	H	H	H	M	H
	Develop buffer strips to reduce fine sediments	M	M	M	M	M
	Develop natural vegetation on buffer strips	H	H	H	M	H

Measure category	Measure	Relevance	Effect in-channel	Effect floodplain	Costs	Prioritisation
River planform	Re-meander water course	M	M	M	H	M
	Widening or re-braiding of water course	H	H	H	M	H
	Create a shallow water course	H	H	H	M	H
	Narrow over-widened water course	H	H	H	M	H
	Create low-flow channels	H	H	H	M	H
	Allow/initiate lateral channel migration	H	H	H	M	H
	Create secondary floodplain	H	H	H	M	H
Floodplain	Reconnect backwaters, oxbow-lakes, wet-lands	H	H	H	M	H
	Create backwaters, oxbow-lakes, wetlands	H	H	H	M	H
	Lower embankments, levees or dikes	H	M	M	L	M
	Replace embankments, levees or dikes	H	M	M	L	M
	Remove embankments, levees or dikes	H	M	M	L	M
	Remove vegetation	L	L	M	L	L

Problems and constraints with common restoration practice

The most often applied measure in anastomosing, lowland rivers is lowering the floodplain in combination with a shallow stream bed whereby the stream can shape the floodplain, rewet it and form multiple channels. remeandering. Active anastomosing did not occur yet. The major problem is the rise of te ground water table in the floodplain, necessary for recovery processes but mostly limited by other societal interests.

Hydrological measures are more often only applied along river stretches in low to zero slope areas without considering the hydrological dynamics that results from catchment wide activities, like drainage, water abstraction and paved surfaces.

Giving room for free swamp forest development also meets a lot of resistance from other users of the floodplain.

Promising and new measures

In general, multiple channels do not differ much in in-channel features compared to single channels. The most important difference are of course the semi-aquatic to terrestrial patches between the channels. Restoring anastomosing, lowland rivers implies an integrated restoration of the floodplain and extends much further into a catchment in comparison to a single-thread river.

Restoration of small, anastomosing, lowland rivers is until now an underestimated possibility for lowland river valley restoration. By restoring processes that create a two to multiple channel pattern in a rewetted area or by even actively creating a multiple channel pattern three major objectives can be reached at the same time; 1) the rewetted area can serve as a large water retention area for water safety downstream, 2) the multiple channel network provides a higher water flow through area then one single channel and has a has a higher width : depth ratio, 3) the biodiversity in a gradient of channels, swampy banks and wet higher ‘islands’ is much higher.

The chances of reaching a stable multiple channel network that is controlled by vegetation, as is the case for small, anastomosing, low energy rivers in the lowlands, is highest in stretches of the river where the slope is low to near zero. Historically, here swamps or bogs occurred. Remains of former bogs are recognizable in stream valley-peatlands. Such swampy areas can develop either in anastomosing rivers or in flow-through swamps depending on the flood frequency and intensity.

Restoring small, low energy, anastomosing rivers with either two or more channels starts with a catchment analysis. A number of features of these systems should be kept in mind to reach a successful approach:

- A stable anastomosing channel system with biotic channel spanning obstructions.
- Overbank flows occurs regularly, for longer duration, and with larger magnitude compared to a meandering system.
- Avulsions are the main mechanism for channel change; primary and secondary avulsions occur with new dam formation, like obstructions through vegetation overgrowth, and during overbank flows.
- Channel migration is a secondary mechanism for channel change; less cohesive sediment and less stabilizing vegetation in a more or less continuous wet environment (water almost year round at or above mowing level) create a more dynamic environment.
- There is more sediment deposited in the channel behind plant, logs or beaver dams and much fine sediment is deposited in the floodplain as a result of more frequent overbank flows; sedimentation is heterogeneous.
- There are lower energy flows (less high peak flows), but overbank flows affect a larger area and saturate the ground.
- The riparian zone extends across the valley, past the channel closest to valley edge; a higher water table across the valley supports riparian vegetation.
- The wetter environment promotes growth of riparian shrubs and graminoids.
- Fine sediment increases bank cohesion; a mix of riparian and shrubs and graminoids increases bank stability.

To create a more riparian wetland type of environment along a very low gradient trajectory of the small stream, a downstream obstruction is needed. Such obstruction can be natural or engineered (Figure 1).

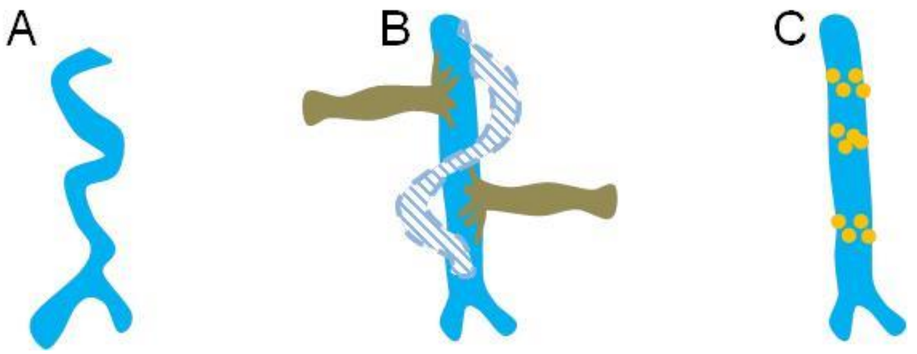

Figure: A flow retarding or obstructing structure can be a meandering river stretch (A), a by introduced logs initiated meandering stretch with a preferably smaller wet area (B), or a weir like construction made of a cascade from stones or logs that simultaneous act as fish passage.

The anastomosing channel system can occur in different shapes (Figure 2).

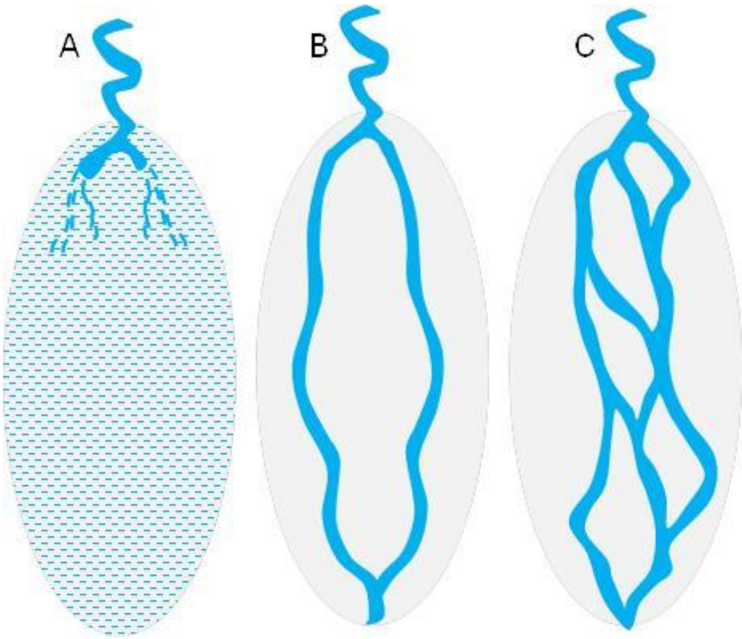

Figure: The anastomosing river valley can look like a flow through wetland either or not forested (A), a wetland either or not forested with two channels (B), or a wetland either or not forested with an anastomosing channel network.

Monitoring scheme

Monitoring schemes should follow some basic principles that apply to all river types:

- Biotic as well as abiotic variables should be monitored. The restoration measures might have succeeded to create the desired habitats but the effect on biota might be limited due to other pressures at larger scales which have not been addressed in the restoration project.
- In-channel, riparian, as well as floodplain conditions should be monitored. Besides the biological quality elements relevant for the Water Framework Directive, restoration can also have positive effects on other semi-aquatic and terrestrial organism groups, like ground beetles and floodplain vegetation. Indeed, there is empirical evidence that effects on other organism groups can be larger.
- Monitoring has to be conducted at appropriate spatial and temporal scales that reflect (i) the habitat needs of the organisms (e.g. monitoring microhabitat substrate patches for macroinvertebrates, mesohabitat features for fish), (ii) all life stages (e.g. monitoring in-channel and riparian habitats for macroinvertebrates with terrestrial life-stages), (iii) and the reproductive cycle as well as dispersal abilities (long-term monitoring to also cover effects of restoration on long-lived species and weak dispersers).
- Looking at the spatial and time scale of many current restoration measures macro-invertebrates are most suited for river monitoring. Fish population are strongly managed and reflect larger scale conditions, macrophytes bear a long history as they disappear only slowly and algae reflect to short time scales and very, very

local conditions. Floodplains are large scaled and best be monitored by vegetation. Riparian zone can be monitored by using vegetation or carabid beetles.

- A Before-After-Control-Impact design should be applied to allow disentangling the effect of restoration from general trends in the whole river or catchment.
- However, the final selection of the organism groups, and spatial / temporal scales monitored strongly depends on the objectives and applied measures. Of course, it is reasonable to focus on the abiotic and biotic variables and scales that potentially have been affected by the restoration measures (e.g. in-channel habitat conditions by in-channel measures).
- Monitoring results should be used for adaptive management, i.e. to react on unanticipated effects and trends, and this should be included in the planning from the beginning (“Plan-B”).

For further reading and practical guidelines we refer to the handbook of the River Restoration Centre (River Restoration Centre 2011).

The relevance of a variable at the scale of the river, riparian zone and floodplain scored in comparison to other variables within this river type (No = no relevance, L = low relevance, M = moderate relevance, H = high relevance)

Variable group	**Variable**	**River**	**Wetland zone**	**Floodplain**
River and wetland hydrology		H	H	H
Wetland and in-river hydraulics		H	H	L
Floodplain and wetland morphology		L	H	M
Wetland and in-channel morphology	Profile (longitudinal, transversal)	H	No	M
	Meso-/micro-structures	M	M	No
Chemistry	Nutrients	H	H	L
	Toxicants	H	H	L
	Others			
Biology	Algae	L	L	No
	Macrophytes	M	H	No
	Macroinvertebrates	H	H	No
	Fish	M	L	No
	Floodplain/riparian vegetation	L	H	H
	Terrestrial fauna	No	H	M

Fact sheet: Medium-large, anastomosing, lowland rivers

General description

Anastomosing channels are a subcategory of the island-braided channel pattern with interconnected, coexisting channels separated by terraces or floodplain islands, with erosion-resistant cohesive banks, gentle gradient, and relatively low width-depth ratios of individual channels. The distinguishing feature of anastomosing channels is that hydraulic and sediment transport dynamics of each channel are independent of the other channels. Anastomosing channels are generally stable in the short term with cohesive banks, low width to depth ratio channels, and gentle channel gradient that exhibit little or no lateral migration. The dominant channel migration process is avulsion.

Valley- and planform	The valley has a flat bottom that can be wide to very wide with gentle slope margins. The channel planform consists of a multiple channel river characterized by vegetated or otherwise stable alluvial islands that divide flows. Each channel in itself can have a straight/sinuous to a more meandering planform. Primary, secondary and lost channels can be present.
Hydrology	In the natural situation entrenchment of the channels is reasonable; the channels are relatively narrow and deep. The floodplain is completely inundated during floods. Anastomosing, large, lowland rivers can be permanent or some channels maybe intermittent. The hydrograph is moderately dynamic and most of the time there is bank full discharge. The floodplain islands are often flooded for a few weeks or more during water level rises.
Morphology	The valley is more often largely covered with peat and organic deposits (organic wetland). The channels are laterally stable due to stabilizing vegetation in combination with relatively low stream power. The erosion-sedimentation processes are only local. Channel formation is slow (patterns can last for >100 years). Changes are due to channel sedimentation, the formation of vegetation blocking the flow through or ineffective flow due to the very low channel gradient. The channel banks are often quite vertical, formed by plant roots in a 'grill-like' shape. The river bottom is dominated by sand and organic silt (dark organic slurry), and fine and coarse particulate organic matter (e.g. dead helophytes), clasts of peat, and local stands of vascular hydrophytes. The floodplain islands are only slightly elevated over the mean water level.
Chemistry	Depending on the upstream geology the floodplain has become organic (peat formation) and the pH can vary from 5.5 to 7. The water quality is mesotrophic.
Wetland zone	The wetland consists of densely vegetated marshy grounds that are dominated by rushes, sedges, reeds and gramnoids, locally a deciduous swamp forest (Salicetum) could develop but large parts of the area are without trees due to the high water levels.

Photo: Large, anastomosing, lowland river (Narew) in Poland.

Pressures

Major pressures

The prevailing hydromorphological pressure in large, anastomosing, lowland rivers is drainage of the floodplain and channelization of the main channel with filling other channels. These changes go in combination with flow alteration (resulting from impoundment and drainage of agricultural and urban lands upstream and along the sides in the catchment), and alteration of the floodplain vegetation.

Score of pressure level imposed on large, anastomosing, lowland rivers categorised according to pressure category and pressure, respectively (score in comparison to other pressures within this river type: No = no pressure/stress, L = low pressure/stress, M = moderate pressure/stress, H = high pressure/stress).

Pressure category	**Pressure**	**Score**
Point sources	Point sources	H
Diffuse sources	Diffuse sources	H
Water abstraction	Surface water abstraction	M
	Groundwater abstraction	M
Flow alteration	Discharge diversions and returns	M
	Interbasin flow transfer	No
	Hydrological regime modification including erosion due to increase in peak discharges	H
	Hydropeaking	No

Pressure category	Pressure	Score
	Flush flow	M
	Impoundment	H
Barriers/Connectivity	Artificial barriers upriver from the site	M
	Artificial barriers downriver from the site	M
Channelization	Channelisation / cross section alteration (e.g. deepening) including erosion due to this	H
	Sedimentation	M
Bank degradation	Bank degradation	H
Habitat degradation	Alteration of riparian wetland vegetation	H
	Alteration of in-rivers habitat	L
Others	Maintenance	H
	Exotic species	L

Problems and constraints for river restoration

Floodplain drainage and channelization strongly lower the ground and surface water levels and results in a more dynamic hydrograph. Side channels are filled in, will become intermittent or will dry up. Due to downstream channelization the main channel will incise with further water level lowering and drying up of the floodplain. More dynamic flows will scour the river bed and change it to a more mineral single thread system.

Drying of the floodplain reduces the bank stability and the amount of organic material from decaying macrophytes in the channels. Incision of the main channel bed due to channelization and flow alteration will strongly reduce the hydrological connectivity between river and wetland floodplain.

Depending on the catchment (ground)water abstractions can also play an important role in river flow alteration. Groundwater abstractions may lower the discharge of the river, thereby decreasing the flow velocity and water depth with further terrestrialisation of smaller channels.

In many cases maintenance consisting of removing of aquatic vegetation and/or dredging is performed to counteract effects of macrophyte development and channel obstruction.

Apart from hydromorphological pressures these large, low gradient, lowland rivers often suffer from eutrophication and organic pollution resulting from a high proportion of agricultural land use upstream in the catchment.

Measures

Common restoration practice

There is little literature available on measures taken to recover and restore large, anastomosing, lowland rivers. Probably this is because of the high costs of floodplain wide measures that include either buying of land or changing land use due to a strong raise in ground water level. Thus, measures that deal with the whole floodplain are rare, but when taken always in combination combined with in river or channel planform measures. The length of a restored stretch must be long and cover large parts of the valley. In ideal cases the processes that result in multiple channels are restored. Knowledge on active multiple channel initiation lacks.

Score per measure category/measure of relevance, effect in-river, effect on the flood-plain and costs the measure in comparison to other measures within this river type (No = no relevance or effect, L = low relevance or effect, M = moderate relevance or effect, H = high relevance or effect of the measure) and indication a prioritisation of measures (L = low priority, M = moderate priority, H = high priority).

Measure category	Measure	Relevance	Effect in-channel	Effect floodplain	Costs	Prioritisation
Decrease pollution	Decrease point source pollution	M	L	M	H	M
	Decrease diffuse pollution input	H	M	H	H	H
Water flow quantity	Reduce surface water abstraction	H	M	H	L	H
	Improve water retention	H	M	H	H	H
	Reduce groundwater abstraction	H	M	H	M	H
	Improve water storage	H	M	H	H	H
	Increase minimum flow	H	H	H	H	H
	Water diversion and transfer	M	M	M	H	M
	Recycle used water	M	M	M	H	M
	Reduce water consumption	M	M	M	L	M
Sediment quantity	Add/feed sediment	L	L	L	M	L
	Reduce undesired sediment input	L	L	L	L	L
	Prevent sediment accumulation	L	L	L	M	L
	Improve continuity of sediment transport	M	M	M	M	M
	Trap sediments	L	L	L	M	L
	Reduce impact of dredging	M	M	L	M	H
Flow dynamics	Establish natural environmental flows	H	H	H	H	H
	Modify hydropeaking	No				
	Increase flood frequency and duration	H	M	H	H	H
	Reduce anthropogenic flow peaks	H	M	H	H	H
	Shorten the length of impounded reaches	L	L	No	L	L
	Favour morphogenic flows	M	M	M	M	M
Longitudinal connectivity	Install fish pass, bypass, side channels*	H*	M*	H*	L*	H*
	Install facilities for downriver migration	No				
	Manage sluice, weir, and turbine operation	No				
	Remove barrier	H	H	H	M	H
	Modify or remove culverts, syphons, piped rivers	H	H	H	M	H

Measure category	Measure	Relevance	Effect in-channel	Effect floodplain	Costs	Prioritisation
In-channel habitat conditions	Remove bed fixation	H	H	H	M	H
	Remove bank fixation	H	H	H	M	H
	Remove sediment	L	L	L	M	L
	Add sediment (e.g. gravel)	L	L	L	M	L
	Manage aquatic vegetation	M	M	M	H	M
	Remove in-channel hydraulic structures	H	H	H	M	H
	Creating shallows near the bank	L	L	L	M	L
	Recruitment or placement of large wood	M	M	L	H	H
	Boulder placement	No				
	Initiate natural channel dynamics	M	M	M	L	H
	Create artificial gravel bar or riffle	L	L	No	M	L
Riparian zone	Develop buffer strips to reduce nutrients	M	M	M	M	M
	Develop buffer strips to reduce fine sediments	M	M	M	M	M
	Develop natural vegetation on buffer strips	No				
River planform	Re-meander water course	No				
	Widening or re-braiding of water course	H	H	H	M	H
	Create a shallow water course	M	M	M	M	M
	Narrow over-widened water course	M	M	M	M	M
	Create low-flow channels	H	H	H	M	H
	Allow/initiate lateral channel migration	H	H	H	M	H
	Create secondary floodplain	H	H	H	M	H
Floodplain	Reconnect backwaters, oxbow-lakes, wetlands	H	H	H	M	H
	Create backwaters, oxbow-lakes, wetlands	H	H	H	M	H
	Lower embankments, levees or dikes	H	M	M	L	M
	Replace embankments, levees or dikes	H	M	M	L	M
	Remove embankments, levees or dikes	H	M	M	L	M
	Remove vegetation	L	L	M	L	L

Problems and constraints with common restoration practice

The major problem is the rise of the ground water table in the floodplain, necessary for recovery processes but mostly limited by other societal interests. Thus, the most often applied measure in large, anastomosing, lowland rivers is improving the water table in the floodplain. Hereby, the floodplain islands are rewetted. Active anastomosing of a large floodplain did not occur yet.

Hydrological measures are more often only applied along river stretches in low to zero slope areas without considering the hydrological dynamics that results from catchment wide activities, like drainage, water abstraction and paved surfaces.

Another constraint is a high eutrophication level due to fertilisers from agricultural activities. The supply of nutrients can strongly increase plant growth and terrestrialisation.

Giving room for free marshy area development also meets a lot of resistance from other users of the floodplain.

Promising and new measures

In general, the multiple, interconnected, low-gradient, relatively deep and laterally stable channels (stabilised by vegetation) characterise the river aspect. The low gradient valley bottom, the flatness and the small elevation of the floodplain islands over the mean water level in the channels typify the floodplain islands. Here peat formation is not uncommon. Changes in these large anastomosing systems are slow and driven by avulsion favoured by vertical aggradation. The cause of avulsion are more often obstructions formed by plants and preferred sites for new channels are zones with less dense vegetation, e.g. due to animals activity (paths). Restoring large, anastomosing, lowland rivers implies an integrated restoration of the processes described above at the scale of the floodplain and extends much further into a catchment in comparison to a single-thread river.

Restoration of large, anastomosing, lowland rivers is until now a unique possibility for large, lowland river valley restoration. By restoring processes that create a multiple channel pattern in a rewetted area three major objectives can be reached at the same time; 1) the rewetted area can serve as a large water retention area for water safety downstream, 2) the multiple channel network provides a higher water flow through area then one single channel and has a has a higher width : depth ratio, 3) the biodiversity in a gradient of channels, marshy floodplain islands is much higher.

The chances of reaching a stable multiple channel network that is controlled by vegetation, as is the case for large, anastomosing, low energy rivers in the lowlands, is highest in parts of the floodplain were valleys with a gradient of around zero. Historically, here marshy bogs occurred which can amongst others be seen in the upper layer of the soil where peat is deposited.

Restoring large, low energy, anastomosing rivers with a channel network starts with a catchment and floodplain analysis. A number of features of these systems should be kept in mind to reach a successful approach:

- A stable anastomosing channel system with biotic (partly) channel spanning obstructions, like patches of plants that form ‘floating islands’.
- Overbank flows occurs regularly, for longer duration, and with larger magnitude compared to a meandering system.
- Avulsions are the main mechanism for channel change; primary and secondary avulsions occur with new dam formation, like obstructions through vegetation overgrowth (patches of plants that form ‘floating islands’), and during overbank flows.
- Channel migration is a secondary mechanism for channel change; less cohesive sediment and less stabilizing vegetation in a more or less continuous wet environment (water almost year round at or above mowing level) create a more dynamic environment.

- There is more sediment deposited in the channel behind plant, logs or beaver dams and much fine sediment is deposited in the floodplain as a result of more frequent overbank flows; sedimentation is heterogeneous.
- There are lower energy flows (less high peak flows), but overbank flows affect a larger area and saturate the ground.
- The riparian zone extends across the valley, past the channel closest to valley edge; a higher water table across the valley supports riparian vegetation.
- The wetter environment promotes growth of rushes and sedges.
- Reed and other plant roots stabilize the banks.

To restore or newly create a anastomosing channel system through a wetland along a very low gradient trajectory of a river, preferably floodplain remnants are still present and space is available or can be obtained. Restoration can be processes based using the natural hydromorphological processes as illustrated in figures 1 and 2.

Next, the restoration of the hydromorphological infrastructure at the scale of the whole floodplain area is the key to success. In most cases, the anastomosing channel network is reduced to one single channel and measures must be taken to change the channel physical features back by e.g. cleaning the former channel beds (side or secondary channels) by removing the excess of sediment and vegetation that has overgrowing these beds or filled them in and by reconnecting them to the main channel. Additionally, to rise the water level for the entire plain (natural) weir structures, like underwater thresholds made by logs, must be placed. To divert part of water flow from the main channel into the secondary channels wide openings at the diversion points and structures, like deflectors can be very helpful. Another important measure is the reduction of the in-flow of nutrients discharged by diffuse sources, like agricultural activities, upstream. Also turning over the agriculture land use in the riparian area to an extensive form (e.g. hay production needs attention.

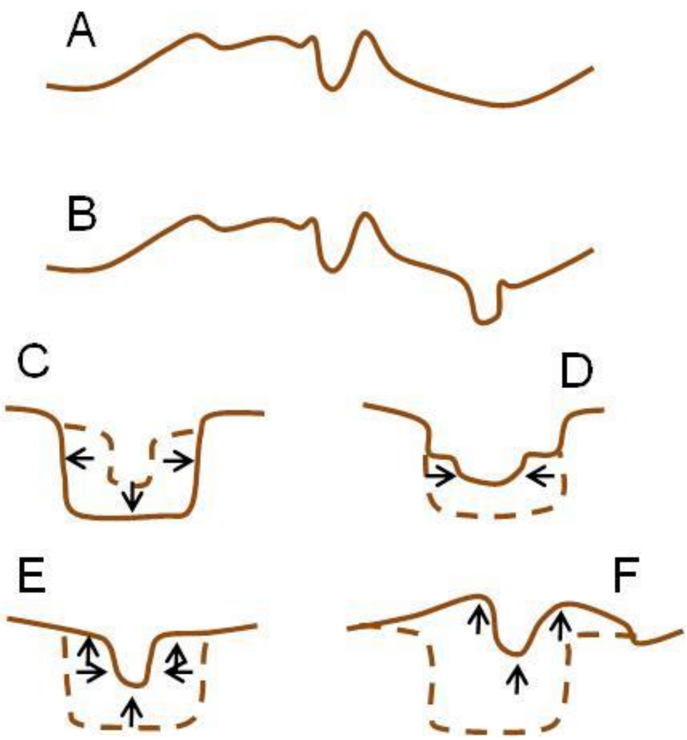

Figure: Six steps in channel evolution of an anastomosing system. A. Wetland cross section with the old channel prior to development of a new channel incision, B. initial incision of the new channel, C. incision and widening of the new channel, D. increased sedi-

ment deposition, E. channel narrowing and sinuosity increase; (f) channel is raised by deposition and natural levees form.

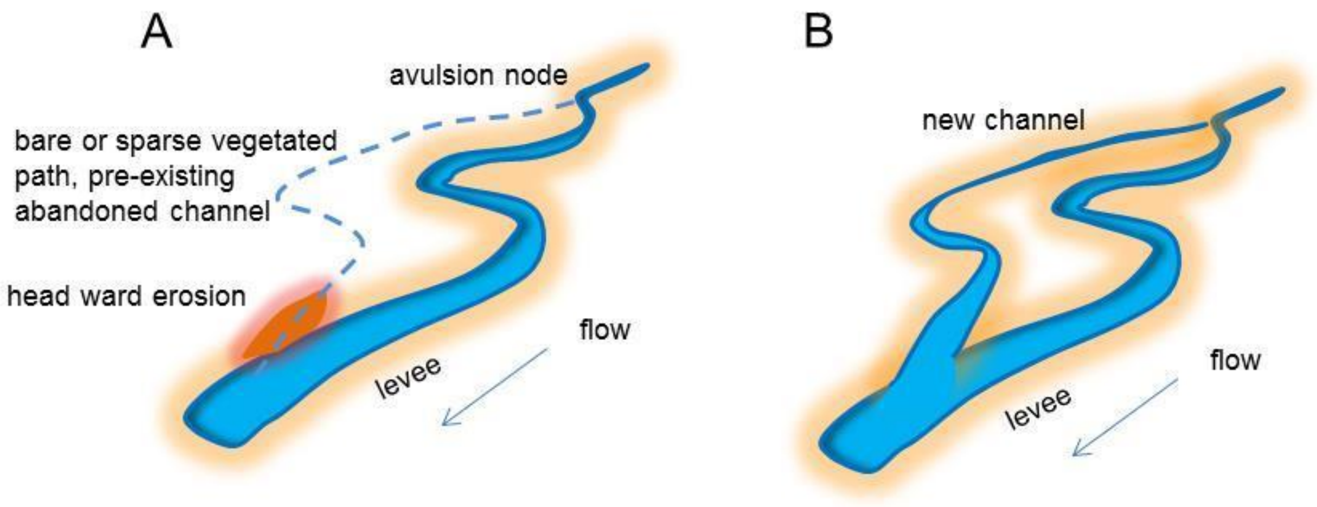

Figure: Establishment of a new channel after the main channel was partially blocked at the avulsion point (A,) and during high flow a new channel is formed and later by head ward erosion is shaped (B).

Restoration of an anastomosing channel network (Figure 3).

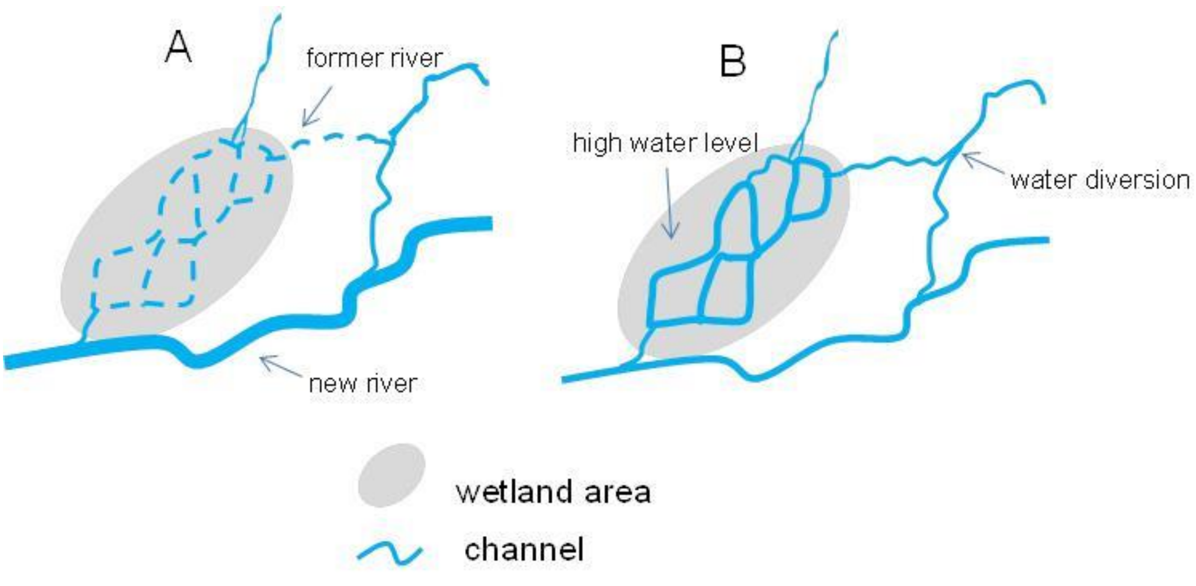

Figure: The anastomosing river valley can be restored by reconnecting and opening old river beds (dotted lines in A), and diverting larger parts of the flow through the wetland (B).

Monitoring scheme

Monitoring schemes should follow some basic principles that apply to all river types:

- Biotic as well as abiotic variables should be monitored. The restoration measures might have succeeded to create the desired habitats but the effect on biota might be limited due to other pressures at larger scales which have not been addressed in the restoration project.
- In-channel, riparian, as well as floodplain conditions should be monitored. Besides the biological quality elements relevant for the Water Framework Directive, restoration can also have positive effects on other semi-aquatic and terrestrial organism groups, like ground beetles and floodplain vegetation. Indeed, there is empirical evidence that effects on other organism groups can be larger.
- Monitoring has to be conducted at appropriate spatial and temporal scales that reflect (i) the habitat needs of the organisms (e.g. monitoring microhabitat substrate patches for macroinvertebrates, mesohabitat features for fish), (ii) all life stages (e.g. monitoring in-channel and riparian habitats for macroinvertebrates with terrestrial life-stages), (iii) and the reproductive cycle as well as dispersal abilities (long-term monitoring to also cover effects of restoration on long-lived species and weak dispersers).
- Looking at the spatial and time scale of many current restoration measures macro-invertebrates are most suited for river monitoring. Fish population are strongly managed and reflect larger scale conditions, macrophytes bear a long history as they disappear only slowly and algae reflect to short time scales and very, very local conditions. Floodplains are large scaled and best be monitored by vegetation. Riparian zone can be monitored by using vegetation or carabid beetles.
- A Before-After-Control-Impact design should be applied to allow disentangling the effect of restoration from general trends in the whole river or catchment.
- However, the final selection of the organism groups, and spatial / temporal scales monitored strongly depends on the objectives and applied measures. Of course, it is reasonable to focus on the abiotic and biotic variables and scales that potentially have been affected by the restoration measures (e.g. in-channel habitat conditions by in-channel measures).
- Monitoring results should be used for adaptive management, i.e. to react on unanticipated effects and trends, and this should be included in the planning from the beginning ("Plan-B").

For further reading and practical guidelines we refer to the handbook of the River Restoration Centre (River Restoration Centre 2011).

The relevance of a variable at the scale of the river, riparian zone and floodplain scored in comparison to other variables within this river type (No = no relevance, L = low relevance, M = moderate relevance, H = high relevance)

Variable group	Variable	River	Wetland zone	Floodplain
River and wetland hydrology		H	H	H
Wetland and in-river hydraulics		H	H	L
Floodplain and wetland morphology		L	H	L
Wetland and in-channel morphology	Profile (longitudinal, transversal)	H	L	M
	Meso-/micro-	M	M	No

Variable group	Variable	River	Wetland zone	Floodplain
	structures			
Chemistry	Nutrients	H	H	M
	Toxicants	H	H	M
	Others			
Biology	Algae	H	M	No
	Macrophytes	H	H	No
	Macroinvertebrates	H	H	No
	Fish	H	M	No
	Floodplain/riparian vegetation	L	H	L
	Terrestrial fauna	No	M	L

Fact sheet: Small, single- and multi-thread, mid altitude rivers

General description

Valley- and planform	Valleys are U-shaped, partly confining the river planform which is mostly sinuous and partly straight or meandering. Due to the small river size, confinement and/or cohesive river banks, channels are usually single-thread.
Hydrology	Naturally, cross-sections are wide and shallow, and the floodplain is inundated several times a year. Most rivers are permanent and the discharge regime is flushy with pronounced high flow events, especially in boreal and continental rivers with snowmelt floods.
Morphology	Alluvial rivers with typical alternating bars, riffle-pool sequences, and irregular banks partly shaped by tree roots. Although dominated by gravel, bed material of varying size in the sand to cobble range may be present, as well as organic substrates like leaves and large amounts of wood which locally form wood jams that might span the entire channel. Sediments are usually well sorted to reflect the diverse flow pattern and bed morphology.
Chemistry	Depending on the geology pH can vary from 6.5 to 8.5. A distinction can be made between siliceous and calcareous rivers, with neutral to weak alkaline pH-values in calcareous rivers (e.g. flysch region) and siliceous rivers being vulnerable to acidification, especially under spruce forest (e.g. boreal rivers).
Riparian zone	The usually narrow floodplain is dominated by deciduous trees, mainly alder and in addition spruce in boreal rivers, which more or less fully shade the river bed.

Photo: Small, single-thread, mid altitude rivers with bed material of varying size and geology: Siliceous rivers dominated by gravel (Central Europe, upper left, photo A. Lorenz) and cobble to boulder (boreal river, upper right), and a calcareous cobble-bed river in a continental region (flysch region, bottom, photo K. Brabec).

Pressures

Major pressures

The small single-thread rivers in lower-mountain areas are affected by multiple-pressures, most of which fall in three categories: First, point sources (e.g. organic pollution) are still the main pressure in some regions (e.g. Eastern Europe). Water quality has substantially improved in other regions (e.g. Central Europe) but recent studies indicate that even moderate water pollution might still affect biota, especially sensitive macroinvertebrate species. Second, diffuse source pollution including nutrients and fine sediment input. Third hydromorphological alterations, especially missing riparian vegetation, bank fixation, narrowing / entrenchment, and straightening, as well as migration barriers and associated upstream impoundments. Moreover, the remaining riparian vegetation and in-channel large wood are often removed during maintenance.

Furthermore, small, single-thread, mid altitude rivers in some regions are affected by very specific pressures. For example, many boreal rivers in Finland and Sweden are still running through forested areas (i.e. catchment-scale land use pressure is much lower compared to e.g. more densely populated mountain regions in Central Europe) but most of them have been channelized for timber floating (straightening and narrowing, removal of boulders and alteration of in-channel habitat diversity).

Score of pressure level imposed on small, single-thread, mid altitude rivers categorised according to pressure category and pressure, respectively (score in comparison to other pressures within this river type: No = no pressure/stress, L = low pressure/stress, M = moderate pressure/stress, H = high pressure/stress).

Pressure category	Pressure	Score
Point sources	Point sources	M to H*
Diffuse sources	Diffuse sources	M to H$^+$
Water abstraction	Surface water abstraction	L
	Groundwater abstraction	L
Flow alteration	Discharge diversions and returns	L
	Interbasin flow transfer	No
	Hydrological regime modification including erosion due to increase in peak discharges	M
	Hydropeaking	No
	Flush flow	L
	Impoundment	M
Barriers/Connectivity	Artificial barriers upriver from the site	H
	Artificial barriers downriver from the site	M
Channelization	Channelisation / cross section alteration (e.g. deepening) including erosion due to this	H
	Sedimentation	M
Bank degradation	Bank degradation	H
Habitat degradation	Alteration of riparian vegetation	H to M$^-$
	Alteration of in-channels habitat	H
Others	Maintenance	M
	Exotic species	L

*differs between regions, high in e.g. Eastern Europe, moderate in e.g. Central Europe
$^+$high if fine sediment input is substantially increased, moderate if only nutrient loads are increased
$^-$differs between regions, high in Central Europe, moderate in boreal rivers

Problems and constraints for river restoration

Bank fixation limits (lateral) channel dynamics which naturally would be high due to the relatively high stream power.

In free flowing sections, bed substrate coarsens and armouring layers develop due to the high flow velocities in the narrowed and deepened cross-sections. This is especially a problem in gravel-bed rivers with a wide range of grain sizes (poorly sorted substrate), which are prone to develop armour layers. Moreover, the interstitial spaces are filled with fine sediment eroded from non-forested clear-cuts, agricultural areas or trampled river banks. Alternating bars and associated pool-riffle sequences are rare due to the low channel width and sediment deficit caused by upstream barriers. This results in a (non-natural) stable plane-bed morphology. Sediments are packed, coarse, and clogged with fine sediment. Due to the armour layers, bed-material is only mobilized during very high flow events and hence, natural sediment- and morphodynamics are limited. In addition, the lack of large wood results in a uniform channel morphology and uniform high flow velocities and water depth.

In impounded sections, coarse sediment is deposited, causing a sediment deficit downstream. Moreover, also fine sediment is accumulated and in addition to the low flow velocities does not provide any habitat for typical species inhabiting fast-flowing gravel-bed rivers.

Furthermore, missing riparian vegetation reduces the input of organic matter (e.g. leaves, large wood), which is easily transported downstream due to the limited retention capacity of the uniform cross-section. Moreover, missing riparian vegetation reduces shading, resulting in higher water temperatures and increased temperature dynamics.

Measures

Common restoration practice

Most of the restoration projects in small, single-thread, mid altitude rivers applied in-channel measures to increase habitat complexity (~80%), most frequently by removing bed and bank fixation and adding large wood and boulders. Many projects did also aim to restore a more natural planform (~40%) by e.g. remeandering or developed a riparian buffer strip (~30%), while measures to explicitly restore natural sediment dynamics (e.g. by adding sediment, restoring natural sediment transport or limiting fine sediment input) are very rarely applied (~1%).

Score per measure category/measure of relevance, effect in-channel, effect on the floodplain and costs the measure in comparison to other measures within this river type (No = no relevance or effect, L = low relevance or effect, M = moderate relevance or effect, H = high relevance or effect of the measure) and indication a prioritisation of measures (L = low priority, M = moderate priority, H = high priority).

Measure category	Measure	Relevance	Effect in-channel	Effect floodplain	Costs	Prioritisation
Decrease pollution	Decrease point source pollution	M	M	L	H	M
	Decrease diffuse pollution input	H	H	M	H	H
Water flow quantity	Reduce surface water abstraction	L	L	L	L	L
	Improve water retention	M	M	H	H	M
	Reduce groundwater abstraction	L	L	L	M	L
	Improve water storage	M	M	M	H	L
	Increase minimum flow	M	M	M	H	M
	Water diversion and transfer	L	L	No	L	L
	Recycle used water	L	L	No	L	L
	Reduce water consumption	L	L	No	L	L
Sediment quantity	Add/feed sediment	H	M	L	M	H
	Reduce undesired sediment input	M	M	L	M	M
	Prevent sediment accumulation	No				
	Improve continuity of sediment transport	M	M	No	M	M
	Trap sediments	No				
	Reduce impact of dredging	L	L	No	L	L
Flow dynamics	Establish natural environmental flows	M	M	M	M	M
	Modify hydropeaking	No				
	Increase flood frequency and duration	L	L	M	H	M
	Reduce anthropogenic flow peaks	M	M	L	H	M
	Shorten the length of impounded reaches	L	L	No	M	L
	Favour morphogenic flows	M	M	L	M	M
Longitiudinal connectivity	Install fish pass, bypass, side channels	M	H	No	M	M
	Install facilities for downriver migration	L	M	No	M	L
	Manage sluice, weir, and turbine operation	No				
	Remove barrier	M	M	L	M	M
	Modify or remove culverts, syphons, piped rivers	L	L	No	M	L
In-channel habitat conditions	Remove bed fixation	M	M	No	M	M
	Remove bank fixation	M	M	L	M	M
	Remove sediment	L	L	No	M	L

Measure category	Measure	Relevance	Effect in-channel	Effect floodplain	Costs	Prioritisation
	Add sediment (e.g. gravel)	M	M	No	M	M
	Manage aquatic vegetation	L	L	L	M	L
	Remove in-channel hydraulic structures	L	L	No	M	L
	Creating shallows near the bank	L	L	No	L	L
	Recruitment or placement of large wood	H	H	L	M	H
	Boulder placement	L	L	No	M	L
	Initiate natural channel dynamics	H	H	M	L	H
	Create artificial gravel bar or riffle	M	M	No	M	M
Riparian zone	Develop buffer strips to reduce nutrients	H	H	H	M	H
	Develop buffer strips to reduce fine sediments	H	H	M	M	H
	Develop natural vegetation on buffer strips	H	H	H	M	H
River planform	Re-meander water course	M	M	L	H	M
	Widening or re-braiding of water course	L	M	M	H	L
	Create a shallow water course	M	M	M	H	M
	Narrow over-widened water course	L	L	L	M	L
	Create low-flow channels	L	L	L	M	L
	Allow/initiate lateral channel migration	H	H	L	L	H
	Create secondary floodplain	M	L	M	H	M
Floodplain	Reconnect backwaters, oxbow-lakes, wetlands	M	L	M	L	M
	Create backwaters, oxbow-lakes, wetlands	L	L	M	M	M
	Lower embankments, levees or dikes	L	L	M	M	L
	Replace embankments, levees or dikes	L	L	M	M	L
	Remove embankments, levees or dikes	L	L	M	M	L
	Remove vegetation	L	L	H	L	L

Problems and constraints with common restoration practice

In general, instream measures in gravel-bed lower-mountain rivers have a higher and positive effect on aquatic organism groups like fish and macroinvertebrates compared to pure planform measures. Especially the placement and recruitment of large wood is an effective restoration measure, e.g. compared to boulder addition to increase macroinvertebrate richness and fish abundance. Moreover, removing bed- and bank fixation can initiate natural channel-dynamics in these rivers with relatively high stream power, leading to a fast increase in habitat diversity. Therefore, the approach to mainly apply instream measures to restore instream habitat complexity is supported by recent research findings. The effect of restoration is especially high in catchments with a relatively high share of forested areas, probably because water quality is usually high in forested catchments (water pollution and fine sediment not constraining restoration effects), riparian vegetation is present and has beneficial effects on biota (e.g. large wood input, shading), and source populations are present to colonize the restored habitats.

However, variability of restoration effects is high and several projects had no or even negative effects. For example, large wood and boulder addition had very limited or no effects in forested river sections where large stable substrate was already present (e.g. in boreal rivers in Fenno-Scandinavia). Moreover, heavy machinery was often used which might have detrimental effects like the substantial reduction of bryophyte biomass in boreal rivers. Furthermore, even moderate water pollution and fine sediment input as well as missing source populations might limit restoration effects. Most important, the underlying processes resulting in natural flow and sediment dynamics are rarely restored, which limits the effects of locally restoring forms. As mentioned above, a low channel width and sediment deficit hinders the formation of alternating bars and associated pool-riffle sequences. Such natural flow and sediment dynamics are necessary to sustainably provide loose and clean well-sorted gravel, e.g. as habitat for invertebrates and spawning gravel for fish.

Promising and new measures

The effect of local instream restoration measures in small, single-thread, mid altitude rivers can potentially be improved by (i) ensuring that catchment-scale pressures do not constrain the effects, and (ii) restoring natural flow and sediment dynamics, i.e. processes.

The most important catchment-scale pressures which potentially constrain the effects of local restoration projects are water pollution, fine sediment, and missing source populations. If present, these pressures should be addressed in addition to restoring local habitat conditions.

- There is empirical evidence that even moderate organic pollution might still limit biota, especially macroinvertebrates, and hence, saprobic indices should indicate a good or high status.
- Source populations can be identified based on information from monitoring sites, species distribution models or expert knowledge. Based on present knowledge on fish dispersal, source populations should be at a maximum distance of about 5 km up- or downstream of the restored section. Fish dispersal models have recently been developed to assess the re-colonization potential for different fish species in detail (e.g. FIDIMO). For macroinvertebrates, source populations should be located upstream since they are less mobile than fish and purely aquatic invertebrates (hololimnic species) mainly disperse by downstream drift. Moreover, source populations should be located less than 1.0 - 2.5 km upstream of the restored sections.
- Several methods are available to quantify the fine sediment content and oxygen depletion in gravelly sediments (e.g. freeze-cores, infiltration bags, dissolved oxygen logger). There are also less labour-intensive and costly methods available for a rough assessment of fine sediment stress like (i) visual estimates of percentage cover, (ii) the shuffle index (assessing the degree and duration of reduced visibility above a white tile placed on the river bed caused by the plume resulting from disturbing the sediment upstream), and (iii) the nail test (length of rusted part of nails placed in the sediment indicating well oxygenated conditions and grey parts oxygen depletion). Moreover, some biological metrics have recently been developed indicating fine sediment stress.

Restoring forms like gravel bars has very limited effects and is not sustainable if the underlying processes which rejuvenate these channel features have not been restored as well. To ensure that alternating bars and associated riffle-pool sequences develop and persist, it is necessary to restore an adequate channel-width, natural sediment loads and dynamics, and a natural flow regime. If the present channel-width is too low to allow the formation of free stable alternating bars, the non-natural plane-bed morphology will even persist if natural sediment transport has been restored. Therefore, it is crucial to first restore a natural channel width. Methods to asses if the present low channel width constrains the formation of free stable alternating bars are described in literature. Second, if there is a sediment deficit, river continuity for sediment transport has to be restored or - at least - sediment has to be continuously added to mitigate the sediment deficit. Third, the flow regime must not be substantially altered e.g. by increased peak flows from impervious areas.

Monitoring scheme

Monitoring schemes should follow some basic principles that apply to all river types:

- Biotic as well as abiotic variables should be monitored. The restoration measures might have succeeded to create the desired habitats but the effect on biota might be limited due to other pressures at larger scales which have not been addressed in the restoration project.
- In-channel, riparian, as well as floodplain conditions should be monitored. Besides the biological quality elements relevant for the Water Framework Directive, restoration can also have positive effects on other semi-aquatic and terrestrial organism groups, like ground beetles and floodplain vegetation. Indeed, there is empirical evidence that effects on other organism groups can be larger.
- Monitoring has to be conducted at appropriate spatial and temporal scales that reflect (i) the habitat needs of the organisms (e.g. monitoring microhabitat substrate patches for macroinvertebrates, mesohabitat features for fish, consider habitats at river margins and in floodplain like side channels and ponds), (ii) all life stages (e.g. monitoring in-channel and riparian habitats for macroinvertebrates with terrestrial life-stages), (iii) the reproductive cycle as well as dispersal abilities (long-term monitoring to also cover effects of restoration on long-lived species and weak dispersers), and (iv) seasonal changes and patterns that occur during the year.
- Looking at the spatial and time scale of many current restoration measures macro-invertebrates are most suited for river monitoring. Fish population are strongly managed and reflect larger scale conditions, macrophytes bear a long history as they disappear only slowly and algae reflect to short time scales and very, very local conditions. Floodplains are large scaled and best be monitored by vegetation. Riparian zone can be monitored by using vegetation or carabid beetles.
- A Before-After-Control-Impact design should be applied to allow disentangling the effect of restoration from general trends in the whole river or catchment.
- However, the final selection of the organism groups, and spatial / temporal scales monitored strongly depends on the objectives and applied measures. Of course, it is reasonable to focus on the abiotic and biotic variables and scales that potentially have been affected by the restoration measures (e.g. in-channel habitat conditions by in-channel measures).
- Monitoring results should be used for adaptive management, i.e. to react on unanticipated effects and trends, and this should be included in the planning from the beginning ("Plan-B").

For further reading and practical guidelines we refer to the handbook of the River Restoration Centre (River Restoration Centre 2011).

The relevance of a variable at the scale of the river, riparian zone and floodplain scored in comparison to other variables within this river type (No = no relevance, L = low relevance, M = moderate relevance, H = high relevance)

Variable group	Variable	River	Riparian zone	Floodplain
River hydrology		H	M	M
In-channel hydraulics		H	M	No
Floodplain morphology		L	L	M
In-channel morphology	Profile (longitudinal, transversal)	H	M	M
	Meso-/micro-structures	H	L	No
Chemistry	Nutrients	H	M	L
	Toxicants	H	M	L
	Others			
Biology	Algae	L	No	No
	Macrophytes	M	L	No
	Macroinvertebrates	H	L	No
	Fish	H	L	No
	Floodplain/riparian vegetation	L	M	M
	Terrestrial fauna	No	M	L

Fact sheet: Medium-large, single- and multi-thread, mid altitude rivers

General description

Valley- and planform	Usually unconfined rivers in wide valleys. River planform is extremely varied, including braided, island braided, and high-energy anabranching multithread types through transitional wandering planforms to sinuous and meandering single thread types.
Hydrology	Naturally, cross-sections are wide and shallow, and the floodplain is inundated several times a year. Rivers are permanent (except for the Mediterranean region) and the discharge regime is often flashy with pronounced high flow events.
Morphology	In their natural state, these alluvial rivers can adopt widely-varying morphologies. A sequence of channel patterns occurs as river slope / energy and thus sediment dynamics decrease, bed material becomes finer, bar stability increases (indicated by vegetation encroachment), bank strength increases (influenced by sediment fining and cohesion and vegetation reinforcement), and width and the number of bars in a typical cross section decreases. Braiding is typical of relatively high energy rivers and is usually found where the supply of sediment is high. Braiding rivers display relatively wide bankfull channels with multiple, mainly unvegetated, bars in their cross-section separating multiple flowing channels during low flow conditions. If sufficient bar surfaces become stabilised by vegetation and wood, finer sediment is retained and the vegetated areas grow and form an island-braided pattern, ultimately leading to a high-energy anabranching pattern when the vegetated area exceeds the area of unvegetated bar sediments. A similar high-energy anabranching pattern can develop when parts of the floodplain are excised by avulsion (e.g. caused by wood jams or sediment accumulations). These islands consist of floodplain material, are more stable and above bankfull stage (in contrast to islands of the anabranching pattern evolving from braid bars) and can develop in rivers with less energy than even the transitional wandering rivers described below (but still much higher stream power compared to the low-energy anabranching silt-bed rivers). As stream power decreases, bed material becomes finer and the banks are more able to resist erosion, especially when they are well-vegetated. As a result, the bankfull river width tends to narrow, the number of bars in a typical bankfull channel cross section decreases, revealing planform types ranging from transitional wandering patterns, which show a mix of single thread sections and sections with mid-channel islands, and relatively mobile single-thread sinuous to meandering types. In these single thread rivers, sediment accretion on the inside of bends leads to the formation of one free point-bar on the inside of each bend and bank erosion and scour to form a pool at the outer bend. The bends are connected by relatively straight sections containing riffle bed forms at the inflection points.
Chemistry	Depending on the geology pH can vary. A distinction can be made between siliceous and calcareous rivers, with the siliceous rivers being vulnerable to acidification.
Riparian zone	The floodplain is dominated by deciduous trees mainly *Alnus* in the upper catchment and *Salix* in the lower catchment, with smaller parts of the channel-bed being shaded with increasing river width (especially in braiding rivers).

Photo: Medium-Large, mid altitude rivers with a transitional wandering (top), and high-energy anabranching (bottom, A. Lorenz) channel pattern.

Pressures

Major pressures

The medium-large rivers in lower-mountain areas are mainly affected by three types of pressures: First, point sources (e.g. organic pollution) are still the main pressure in some regions (e.g. Eastern Europe). Water quality has substantially improved in other regions (e.g. Central Europe) but recent studies indicate that even moderate water pollution might still affect biota, especially sensitive macroinvertebrate species. Second, diffuse source pollution including nutrients and fine sediment input. Third hydromorphological alterations: The prevailing morphological pressures are missing riparian vegetation, bank fixation, narrowing / entrenchment, and straightening, as well as migration barriers for biota and sediment, and associated upstream impoundments. Moreover, the remaining riparian and aquatic vegetation and in-channel large wood are often removed during maintenance. In addition to these morphological pressures, there are several severe hydrological alterations like increased peak flows from impervious areas, hydrological changes downstream of reservoirs, and water abstraction (especially in Mediterranean rivers).

Score of pressure level imposed on small, single-thread, mid altitude rivers categorised according to pressure category and pressure, respectively (score in comparison to other pressures within this river type and according to the typical pressure situation: No = no pressure/stress, L = low pressure/stress, M = moderate pressure/stress, H = high pressure/stress).

Pressure category	**Pressure**	**Score**
Point sources	Point sources	M to H*
Diffuse sources	Diffuse sources	H
Water abstraction	Surface water abstraction	L to H+
	Groundwater abstraction	L
Flow alteration	Discharge diversions and returns	L
	Interbasin flow transfer	L
	Hydrological regime modification including erosion due to increase in peak discharges	M
	Hydropeaking	L
	Flush flow	M
	Impoundment	H
Barriers/Connectivity	Artificial barriers upriver from the site	H
	Artificial barriers downriver from the site	M
Channelization	Channelisation / cross section alteration (e.g. deepening) including erosion due to this	H
	Sedimentation	H
Bank degradation	Bank degradation	H
Habitat degradation	Alteration of riparian vegetation	H
	Alteration of in-channels habitat	H
Others	e.g. Maintenance	M
	e.g. Exotic species	M

*differs between regions, high in e.g. Eastern Europe, moderate in e.g. Central Europe

+high in dry Mediterranean region, low in Northern Europe

Problems and constraints for river restoration

Bank fixation limits (lateral) channel dynamics and sediment delivery to the river which naturally would be high due to the relatively high stream power of many mid-altitude rivers.

In free flowing sections, bed substrate coarsens and armouring layers develop due to the high flow velocities and sediment deficit, especially in gravel-bed rivers with a wide range of grain sizes (poorly sorted substrate) and platy sediment, which are prone to develop armour layers. Moreover, the interstitial spaces often become filled with fine sediment because of the lack of mobility of the armoured coarse particles lining the bed surface. In addition, the lack of large wood further contributes to a uniform channel morphology and uniform high flow velocities and water depth.

In impounded sections, coarse sediment is deposited, causing a sediment deficit downstream. Moreover, fine sediment is accumulated in impounded sections and, in addition to the low flow velocities, does not provide any habitat for typical species inhabiting fast-flowing gravel-bed rivers.

Furthermore, missing riparian vegetation reduces the input of organic material (including large wood) and reduces shading. Although the riparian vegetation does not fully shade the river bed, this still affects water temperatures and temperature dynamics.

In addition to these effects on instream habitat conditions, the pressures significantly affect the natural controls that have governed river planform in the past, and these changed controls will continue into the future:

- Some past pressures have caused irreversible changes (e.g. massive deposition of cohesive floodplain sediments during the middle-ages in Central Europe).
- Some rivers have not yet adapted to past anthropogenic pressures or pressures changed over time, and hence, rivers are often on a trajectory of change, adapting to these modifications (e.g. deforestation / forestation of riparian areas and floodplains resulting in river widening / braiding and river narrowing / meandering).
- Some restoration projects are restricted to reach-scale measures and do not address large-scale pressures that affect river planform controls (e.g. hydrological and sedimentological changes).
- Climate change will potentially have an effect on channel forming discharges and in addition, environmental change (land-use changes) on bank stability and sediment loads.

Measures

Common restoration practice

Most of the restoration projects in medium-large, mid altitude rivers have applied in-channel measures to increase habitat complexity (~75%), most frequently by removing bank fixation and creating shallow slow-flowing areas. Most projects have also aimed to restore a more natural planform (~54%), mainly by widening and some by remeandering. Moreover, many projects have developed a riparian buffer strip (~30%) and restored floodplain habitats (~48%), while measures to explicitly restore natural sediment dynamics (e.g. by adding sediment, restoring natural sediment transport or limiting fine sediment input) were rarely applied (~6%).

Score per measure category/measure of relevance , effect in-channel, effect on the floodplain and costs the measure in comparison to other measures within this river type

(No = no relevance or effect, L = low relevance or effect, M = moderate relevance or effect, H = high relevance or effect of the measure) and indication a prioritisation of measures (L = low priority, M = moderate priority, H = high priority).

Measure category	Measure	Relevance	Effect in-channel	Effect floodplain	Costs	Prioritisation
Decrease pollution	Decrease point source pollution	M	M	M	H	M
	Decrease diffuse pollution input	H	H	M	H	H
Water flow quantity	Reduce surface water abstraction	L	L	L	L	L
	Improve water retention	M	M	H	H	M
	Reduce groundwater abstraction	L	L	L	M	L
	Improve water storage	M	M	H	H	M
	Increase minimum flow	L	L	L	M	L
	Water diversion and transfer	L	L	No	L	L
	Recycle used water	L	L	No	L	L
	Reduce water consumption	L	L	No	L	L
Sediment quantity	Add/feed sediment	M	M	L	M	M
	Reduce undesired sediment input	H	H	L	M	H
	Prevent sediment accumulation	No				
	Improve continuity of sediment transport	H	H	No	M	H
	Trap sediments	No				
	Reduce impact of dredging	L	L	No	L	L
Flow dynamics	Establish natural environmental flows	M	M	M	M	M
	Modify hydropeaking	No				
	Increase flood frequency and duration	L	M	M	H	M
	Reduce anthropogenic flow peaks	M	M	L	H	M
	Shorten the length of impounded reaches	M	M	No	M	M
	Favour morphogenic flows	M	M	L	M	M
Longitiudinal connectivity	Install fish pass, bypass, side channels	M	H	No	M	H
	Install facilities for downriver migration	M	M	No	M	M
	Manage sluice, weir, and turbine operation	M	M	No	M	L
	Remove barrier	H	H	L	M	H
	Modify or remove culverts, syphons, piped rivers	L	L	No	M	L
In-channel habitat conditions	Remove bed fixation	M	M	No	M	M
	Remove bank fixation	H	H	L	M	H
	Remove sediment	L	L	No	M	L
	Add sediment (e.g. gravel)	M	M	No	M	M
	Manage aquatic vegetation	L	L	L	L	L
	Remove in-channel hydraulic structures	L	L	No	M	L
	Creating shallows near the bank	M	M	L	M	M
	Recruitment or placement of large wood	H	H	L	M	H
	Boulder placement	L	L	No	M	L
	Initiate natural channel dynamics	H	H	M	L	H
	Create artificial gravel bar or riffle	M	H	No	M	M
Riparian zone	Develop buffer strips to reduce nutrients	H	H	H	M	H
	Develop buffer strips to reduce fine sediments	H	H	M	M	H
	Develop natural vegetation on buffer strips	H	H	H	M	H
River planform	Re-meander water course	M	M	L	H	M
	Widening or re-braiding of water course	M	H	M	H	H
	Create a shallow water course	M	M	M	M	M
	Narrow over-widened water course	L	L	L	M	L

Measure category	Measure	Relevance	Effect in-channel	Effect floodplain	Costs	Prioritisation
	Create low-flow channels	L	L	L	M	L
	Allow/initiate lateral channel migration	H	H	L	L	H
	Create secondary floodplain	M	L	H	H	M
Floodplain	Reconnect backwaters, oxbow-lakes, wetlands	M	L	M	L	M
	Create backwaters, oxbow-lakes, wetlands	M	L	M	M	M
	Lower embankments, levees or dikes	L	L	M	M	L
	Replace embankments, levees or dikes	L	L	M	M	L
	Remove embankments, levees or dikes	L	L	M	M	L
	Remove vegetation	L	L	H	L	L

Problems and constraints with common restoration practice

In general, instream measures in gravel-bed lower-mountain rivers have a higher and positive effect on aquatic organism groups like fish and macroinvertebrates compared to pure planform measures. Especially the placement and recruitment of large wood is an effective restoration measure, for example in comparison with boulder addition, to increase macroinvertebrate richness and fish abundance. Therefore, the approach to mainly apply instream measures to restore instream habitat complexity is supported by recent research findings. The effect of restoration is especially high in catchments with a relatively high share of forested areas, probably because water quality is usually high in forested catchments (water pollution and fine sediment not constraining restoration effects), riparian vegetation is present and has beneficial effects on biota (e.g. large wood input, shading), and source populations are present to colonize the restored habitats.

Furthermore, widening (removing bed and bank fixation, flattening river banks, and in some projects considerably widening the cross-section) is one of the most effective restoration measure, especially for terrestrial and semi-aquatic organism groups like floodplain vegetation, ground beetles, and macrophytes compared to its effect on fish and the low or missing effect on macroinvertebrates. There is some empirical evidence that the missing effect on macroinvertebrates might at least be partly due to the low effect of widening projects on microhabitat / substrate diversity. Although widening generally enhances macro- and mesohabitats which often is visually appealing, it still may fail at increasing microhabitat diversity relevant for macroinvertebrates. Moreover, there is empirical evidence that the high effect on terrestrial and semi-aquatic organism groups is mainly due to the creation of open, non-shaded pioneer habitats like gravel bars and shallow areas. Unfortunately, these habitats may vanish over time (i) if morphodynamic processes have not been restored to rejuvenate them or (ii) the restored channel pattern does not correspond to the planform that naturally would develop given the (altered) controls like discharge, sediment load, and bank stability. The latter is especially true for Central Europe where several winding projects have been carried out where present stream power and/or sediment loads are too low to support a braiding pattern. This is problematic especially because over-widening reduces flow velocities and water depths to the extent that natural form recovery is unlikely or takes an excessively long period. There is empirical evidence that these rivers would rather develop a high-energy anabranching channel planform from floodplain avulsion.

Promising and new measures

The effect of local instream and planform measures in medium-large, mid altitude rivers can potentially be improved by (i) ensuring that catchment-scale pressures do not constrain the effects, (ii) restoring natural sediment dynamics, i.e. processes, and (iii) the restored channel pattern corresponds to the channel planform which would develop naturally given the (altered) controls like discharge, sediment load, and bank stability.

The most important catchment-scale pressures which potentially constrain the effects of local restoration projects are water pollution, excessive fine sediment, coarse sediment deficit, and missing source populations. If present, these pressures should be addressed in addition to restoring local habitat conditions.

- There is empirical evidence that even moderate organic pollution might still limit biota, especially macroinvertebrates, and hence, saprobic indices should indicate a good or high status.
- Source populations can be identified based on information from monitoring sites, species distribution models or expert knowledge. Based on present knowledge, for fish, source populations should be at a maximum distance of about 5 km up- or downstream of the restored section. Fish dispersal models have recently been developed to assess the re-colonization potential for different fish species in detail (e.g. FIDIMO). For macroinvertebrates, source populations should be located upstream since they are less mobile than fish and purely aquatic invertebrates (hololimnic species) mainly disperse by downstream drift. Moreover, source populations should be located less than 1.0 - 2.5 km upstream of the restored sections.
- Several methods are available to quantify the fine sediment content and oxygen depletion in gravelly sediments (e.g. freeze-cores, infiltration bags, dissolved oxygen logger). There are also less labour-intensive and costly methods available for a rough assessment of fine sediment stress like (i) visual estimates of percentage cover, (ii) the shuffle index (assessing the degree and duration of reduced visibility above a white tile placed on the river bed caused by the plume resulting from disturbing the sediment upstream), and (iii) the nail test (length of rusted part of nails placed in the sediment indicating well oxygenated conditions and grey parts oxygen depletion). Moreover, some biological metrics have recently been developed indicating fine sediment stress.
- Removal or modification of upstream channel barriers and bank reinforcements can reinstate the supply of coarse sediment and restore a more natural flow regime, resulting in increased coarse sediment mobility and reduced bed armouring.

Restoring forms like a braiding, transitional wandering, meandering or high-energy anabranching channel patterns or channel features like gravel bars is not sustainable and has very limited effects in the long-term if the respective channel planform is not supported by the present conditions (e.g. discharge, sediment load, riparian vegetation and bank stability) and the underlying processes which rejuvenate the channel features have not been restored as well. Therefore, it is necessary to restore an adequate channel-planform with an adequate channel-width, natural sediment loads and dynamics, and a natural flow regime. For example, if there is a sediment deficit, river continuity for sediment transport has to be restored or - at least - sediment has to be continuously added to mitigate the sediment deficit. Moreover, the flow regime must not be substantially altered e.g. by increased peak flows from impervious areas or reduced peak flows by excessive flow regulation. If these anthropogenic changes cannot be mitigated, the restored channel pattern and features will not persist without continuous interventions.

Therefore, it is crucial to first check if anthropogenic changes of the controls, especially discharge, sediment load, and bank stability, potentially have resulted in a shift of the resulting channel pattern. There are several empirical or semi-physical models to assess the channel-planform based on the given controls, some of which have been compiled in Appendix G of the REFORM deliverable D 2.1, Part 2 (also see e.g. Kleinhans and Van den Berg 2010). Moreover, there are catchment to reach scale methods to assess changes in processes and controls as well as historical trajectories of channel adjustment described in the REFORM deliverable D2.1 Part 1, that can support decisions regarding potentially sustainable restoration designs. In case the models indicate that the river is transitional or might still adjust to historical or recent changes in the controls, restoring processes should be favoured over restoring forms since the risk for failure (created forms being destroyed by channel dynamics) is high. In general, there is an increasing awareness that - if possible - restoring processes (natural morphodynamics including flow regime and sediment transport) and keeping anthropogenic interventions to a minimum is the most sustainable restoration approach. More active restoration approaches might be only necessary where the anthropogenic alterations of the natural processes and controls cannot be mitigated.

Monitoring scheme

Monitoring schemes should follow some basic principles that apply to all river types:

- Biotic as well as abiotic variables should be monitored. The restoration measures might have succeeded to create the desired habitats but the effect on biota might be limited due to other pressures at larger scales which have not been addressed in the restoration project.
- In-channel, riparian, as well as floodplain conditions should be monitored. Besides the biological quality elements relevant for the Water Framework Directive, restoration can also have positive effects on other semi-aquatic and terrestrial organism groups, like ground beetles and floodplain vegetation. Indeed, there is empirical evidence that effects on other organism groups can be larger.
- Monitoring has to be conducted at appropriate spatial and temporal scales that reflect (i) the habitat needs of the organisms (e.g. monitoring microhabitat substrate patches for macroinvertebrates, mesohabitat features for fish, consider habitats at river margins and in floodplain like side channels and ponds), (ii) all life stages (e.g. monitoring in-channel and riparian habitats for macroinvertebrates with terrestrial life-stages), (iii) the reproductive cycle as well as dispersal abilities (long-term monitoring to also cover effects of restoration on long-lived species and weak dispersers), and (iv) seasonal changes and patterns that occur during the year.
- Looking at the spatial and time scale of many current restoration measures, macro-invertebrates are most suited for river monitoring. Fish population are strongly managed and reflect larger scale conditions, macrophytes bear a long history as they disappear only slowly and algae reflect to short time scales and very, very local conditions. Floodplains are large scaled and best be monitored by vegetation. The riparian zone can be monitored by using vegetation or carabid beetles.
- A Before-After-Control-Impact design should be applied to allow disentangling the effect of restoration from general trends in the whole river or catchment.
- However, the final selection of the organism groups, and spatial / temporal scales monitored strongly depends on the objectives and applied measures. Of course, it is reasonable to focus on the abiotic and biotic variables and scales that potentially have been affected by the restoration measures (e.g. in-channel habitat conditions by in-channel measures).
- Monitoring results should be used for adaptive management, i.e. to react on unanticipated effects and trends, and this should be included in the planning from the beginning (“Plan-B”).

For further reading and practical guidelines we refer to the handbook of the River Restoration Centre (River Restoration Centre 2011).

The relevance of a variable at the scale of the river, riparian zone and floodplain scored in comparison to other variables within this river type (No = no relevance, L = low relevance, M = moderate relevance, H = high relevance)

Variable group	**Variable**	**River**	**Riparian zone**	**Floodplain**
River hydrology		H	M	M
In-channel hydraulics		H	M	No
Floodplain morphology		L	L	M
In-channel morphology	Profile (longitudinal, transversal)	H	M	M
	Meso-/micro-structures	H	L	No
Chemistry	Nutrients	H	M	L
	Toxicants	H	M	L
	Others			
Biology	Algae	L	No	No
	Macrophytes	M	L	No
	Macroinvertebrates	H	L	No
	Fish	H	L	No
	Floodplain/riparian vegetation	H	H	H
	Terrestrial fauna	No	H	M

Fact sheet: Boreal medium-large, single-thread, mid altitude rivers

General description

Valley- and planform	Low to medium gradient.
Hydrology	The runoff pattern consists of low flows during the winter months, high spring run-off from snow melt and decreasing discharge during the summer. Depending on the rain and the area another discharge peak may occur during the autumn. The hydrological conditions are stable in the streams at lake outlets.
Morphology	Typically reaches are a series of alternating turbulent and tranquil sections. The turbulent sections have run, riffle, step-pool or cascade bedforms and are dominated by coarse till and bedrock from i.a. glacial deposits and eskers. The tranquil sections, pools and lakes, have slow flow and are dominated of peat and other fine sediments.
Chemistry	Depending of the proportion of organic soils in the catchment the humic content of the water varies a lot from very dark waters from peatland dominated catchments to clear waters partially fed from ground water sources and/or from mineral soils. Even though the rivers are generally quite oligotrophic, the nutrient levels as well as acidity vary greatly depending on the soil and bedrock type.
Riparian zone	The flood plain may be narrow or wide at certain conditions. The wide flood plains have usually fertile soils and have long history of agricultural use. It is occupied with decious species such as birch (*Betula pubescens, Betula pendula*), poplar (*Populus tremula*), willow (*Salix* sp.) and alders (*Alnus glutinosa*, *A. incana*) or coniferous species such as Norway spruce (*Picea abies*).

Pressures

Major pressures

Regulation of rivers and impoundment for hydroelectric power has changed the natural hydrological regimes. The channelization for timber floating in the 19th to mid 20th centuries and flood protection has been a major factor in degrading the riffle habitats, decreasing the water retention capacity of the river bed and altering the natural heterogeneous flow patterns in riffles. Diffuse load from agriculture and forestry is currently the major factor affecting water quality (nutrient levels, organic and inorganic sedimentation) and degrading the ecological status of the rivers.

Score of pressure level imposed on medium-large, boreal single-thread, mid altitude rivers categorised according to pressure category and pressure, respectively (score in comparison to other pressures within this river type: No = no pressure/stress, L = low pressure/stress, M = moderate pressure/stress, H = high pressure/stress).

Pressure category	Pressure	Score
Point sources	Point sources	M
Diffuse sources	Diffuse sources	H
Water abstraction	Surface water abstraction	L
	Groundwater abstraction	L
Flow alteration	Discharge diversions and returns	L
	Interbasin flow transfer	L
	Hydrological regime modification including erosion due to increase in peak discharges	M
	Hydropeaking	L
	Flush flow	L
	Impoundment	M
Barriers/Connectivity	Artificial barriers upstream from the site	M
	Artificial barriers downstream from the site	M
Channelization	Channelisation / cross section alteration (e.g. deepening) including erosion due to this	H
	Sedimentation	M
Bank degradation	Bank degradation	M
Habitat degradation	Alteration of riparian vegetation	L
	Alteration of in-stream habitat	H
Others	Acidification	M
	e.g. Exotic species	L

Measures

The common restoration practice involves restoring the natural morphology of the channel, i.e. rearranging the stream bottom using boulders that have originally been removed from the channel during channelization and creating gravel beds for nursery habitat for salmonids. Returning the boulders to the channels can, in optimal case, restore the natural hydro-morphological conditions for aquatic organisms.

Score per measure category/measure of relevance, effect in-river, effect on the floodplain and costs the measure in comparison to other measures within this river type (No = no relevance or effect, L = low relevance or effect, M = moderate relevance or effect, H = high relevance or effect of the measure) and indication a prioritisation of measures (L = low priority, M = moderate priority, H = high priority).

Measure category	Measure	Relevance	Effect in-river	Effect floodplain	Costs	Prioritisation
Decrease pollution	Decrease point source pollution	M	M	L	H	M
	Decrease diffuse pollution input	H	H	M	M	H
Water flow quantity	Reduce surface water abstraction	L	L	L	M	L
	Improve water retention	H	H	H	M	H
	Reduce groundwater abstraction	L	L	L	M	L
	Improve water storage	L	L	L	H	L
	Increase minimum flow	M	M	M	H	H
	Water diversion and transfer	No				
	Recycle used water	No				
	Reduce water consumption	L	L	No	L	L
Sediment quantity	Add/feed sediment	No				
	Reduce undesired sediment input	M	M	L	M	M
	Prevent sediment accumulation	L	L	L	No	L
	Improve continuity of sediment transport	No				
	Trap sediments	No				
	Reduce impact of dredging	H	M	M	M	H
Flow dynamics	Establish natural environmental flows	M	H	H	H	M
	Modify hydropeaking	M	M	M	H	M
	Increase flood frequency and duration	L	L	L	H	L
	Reduce anthropogenic flow peaks	L	M	M	H	M
	Shorten the length of impounded reaches	L	L	L	H	L
	Favour morphogenic flows	H	H	M	M	H
Longitiudinal connectivity	Install fish pass, bypass, side channels	H	M	No	H	H
	Install facilities for downriver migration	L	L	No	M	L
	Manage sluice, weir, and turbine operation	L	L	No	M	L
	Remove barrier	M	H	L	H	L
	Modify or remove culverts, syphons, piped rivers	L	L	L	M	L
In-channel habitat conditions	Remove bed fixation	L	L	L	No	L
	Remove bank fixation	M	M	M	M	M
	Remove sediment	L	L	No	M	L
	Add sediment (e.g. gravel)	H	M	L	M	H
	Manage aquatic vegetation	L	L	L	L	L
	Remove in-channel hydraulic structures	L	L	L	L	L
	Creating shallows near the bank	L	L	No	L	L
	Recruitment or placement of large wood	H	M	L	L	M
	Boulder placement	H	H	L	L	H
	Initiate natural channel dynamics	H	H	M	M	H
	Create artificial gravel bar or riffle	M	M	No	L	M
Riparian zone	Develop buffer strips to reduce nutrients	H	H	H	L	H
	Develop buffer strips to reduce fine sediments	M	M	M	L	M
	Develop natural vegetation on buffer strips	H	H	H	L	H

Measure category	Measure	Relevance	Effect in-river	Effect floodplain	Costs	Prioritisation
River planform	Re-meander water course	L	L	L	H	L
	Widening or re-braiding of water course	M	M	M	H	M
	Create a shallow water course	M	M	M	M	M
	Narrow over-widened water course	L	L	L	M	L
	Create low-flow channels	M	M	L	M	M
	Allow/initiate lateral channel migration	L	L	L	M	L
	Create secondary floodplain	L	L	L	No	L
Floodplain	Reconnect backwaters, oxbow-lakes, wetlands	L	L	L	L	L
	Create backwaters, oxbow-lakes, wetlands	M	M	M	M	M
	Lower embankments, levees or dikes	M	M	M	M	M
	Replace embankments, levees or dikes	L	L	L	M	L
	Remove embankments, levees or dikes	M	M	M	H	M
	Remove vegetation	L	L	L	L	L

Problems and constraints with common restoration practice

Despite of the extensive restoration programs, the biological responses to hydro-morphological restorations have generally been modest. However, the restoration of riffles has been shown to increase stream bed and flow pattern complexity. Impaired water quality due to land use (agriculture, forestry) in the catchment often prevents achieving the ecological goals of the habitat restorations. Moreover, natural hydro-morphological conditions are often only partially re-established and the natural flooding may not enabled which prevents the natural links between the stream and the riparian zone. The restoration measures also often involve using heavy machinery, which is a major disturbance for the stream ecosystem and has caused considerable reduction of bryophyte biomass. Since the mosses offer a habitat for other biota in the streams, their decline may have delayed the overall ecological recovery. Also minor investing in before-after monitoring has hindered identifying the best restoration practices, the long term responses of the biotic communities and causes of the biotic responses.

Promising and new measures

See the corresponding chapter for boreal small, single-thread, mid altitude rivers.

Monitoring scheme

Monitoring schemes should follow some basic principles that apply to all river types:

- Biotic as well as abiotic variables should be monitored. The restoration measures might have succeeded to create the desired habitats but the effect on biota might be limited due to other pressures at larger scales which have not been addressed in the restoration project.
- In-channel, riparian, as well as floodplain conditions should be monitored. Besides the biological quality elements relevant for the Water Framework Directive, resto-

ration can also have positive effects on other semi-aquatic and terrestrial organism groups, like ground beetles and floodplain vegetation. Indeed, there is empirical evidence that effects on other organism groups can be larger.

- Monitoring has to be conducted at appropriate spatial and temporal scales that reflect (i) the habitat needs of the organisms (e.g. monitoring microhabitat substrate patches for macroinvertebrates, mesohabitat features for fish, consider habitats at river margins and in floodplain like side channels and ponds), (ii) all life stages (e.g. monitoring in-channel and riparian habitats for macroinvertebrates with terrestrial life-stages), (iii) the reproductive cycle as well as dispersal abilities (long-term monitoring to also cover effects of restoration on long-lived species and weak dispersers), and (iv) seasonal changes and patterns that occur during the year.
- Looking at the spatial and time scale of many current restoration measures, macro-invertebrates are most suited for river monitoring. Fish population are strongly managed and reflect larger scale conditions, macrophytes bear a long history as they disappear only slowly and algae reflect to short time scales and very, very local conditions. Floodplains are large scaled and best be monitored by vegetation. The riparian zone can be monitored by using vegetation or carabid beetles.
- A Before-After-Control-Impact design should be applied to allow disentangling the effect of restoration from general trends in the whole river or catchment.
- However, the final selection of the organism groups, and spatial / temporal scales monitored strongly depends on the objectives and applied measures. Of course, it is reasonable to focus on the abiotic and biotic variables and scales that potentially have been affected by the restoration measures (e.g. in-channel habitat conditions by in-channel measures).
- Monitoring results should be used for adaptive management, i.e. to react on unanticipated effects and trends, and this should be included in the planning from the beginning ("Plan-B").

For further reading and practical guidelines we refer to the handbook of the River Restoration Centre (River Restoration Centre 2011).

The relevance of a variable at the scale of the river, riparian zone and floodplain scored in comparison to other variables within this river type (No = no relevance, L = low relevance, M = moderate relevance, H = high relevance)

Variable group	**Variable**	**River**	**Riparian zone**	**Floodplain**
River hydrology		H	H	H
In-river hydraulics		H	M	L
Floodplain morphology		L	L	M
In-channel morphology	Profile (longitudinal, transversal)	H	M	L
	Meso-/micro-structures	H	L	No
Chemistry	Nutrients	H	M	L
	Toxicants	H	M	L
	Others			
Biology	Algae	L	L	No

Variable group	Variable	River	Riparian zone	Floodplain
	Macrophytes	H	L	No
	Macroinvertebrates	H	M	No
	Fish	H	No	No
	Floodplain/riparian vegetation	L	M	M
	Terrestrial fauna	No	M	L

Fact sheet: Small, sinuous-straight highland rivers with bedrock-coarse mixed sediments

General description

Valley- and planform	The valley form varies from a gorge to a V-shaped valley and the channel is mainly characterized by a straight planform.
Hydrology	These rivers are dominated by a discharge maximum at early summer (May, June) due to snow melt; except glacial rivers – see fact sheet 14
Morphology	The morphology of these river types varies according to the dominating bed material and the gradient. Streams with higher gradient are characterized by usually strongly confined and highly stable river beds because of the low erodibility of the bedrock bed and bank material. These, sediment supply-limited, single-thread channels exhibit no continuous alluvial bed, but some alluvial material may be stored in scour holes, or behind flow obstructions such as large boulders. Very coarse bed sediment and large wood pieces – delivered by debris falls, slides and flows – accumulate as colluvial valley fill to form the channel bed. Very low and variable fluvial transport limited by shallow flows. Small, relatively low gradient channels at the extremities of the stream network show mixed bed sediments delivered by less catastrophic hillslope processes than the steep subtype accumulate as colluvial valley fill to form the channel bed. Very low and variable fluvial transport limited by shallow flows. (REFORM D21 Type 1-3).
Chemistry	Depending on the geology, pH can vary from 7 to 8. The trophic level is oligotroph, the saprobic indices are between 1,00 and 1,75 (oligosaprob - β-mesosaprob). A distinction can be made between siliceous and calcareous rivers.
Riparian zone	Due to the narrow valley there is no floodplain developed. The river channel is accompanied mainly by bedrock bank or pioneer vegetation. The valley sides are dominated by typical montane tree species. Above the tree line, alpine meadows, shrubs and sporadic dwarfed trees are predominant.

Photo: Small, sinuous-straight, highland river with bedrock-coarse mixed sediments in Austria (BOKU, IHG).

Pressures

Major pressures

The prevailing hydromorphological pressure in *small, single-thread highland rivers* in the alpine region is flow alteration (impoundment and/or discharge diversions) resulting from hydroelectric power production.

In some cases, large storage basins are fed through major water transfer from other catchments.

Score of pressure level imposed on small, single-thread highland rivers categorised according to pressure category and pressure, respectively (score in comparison to other pressures within this river type: No = no pressure/stress, L = low pressure/stress, M = moderate pressure/stress, H = high pressure/stress).

Pressure category	**Pressure**	**Score**
Point sources	Point sources	L
Diffuse sources	Diffuse sources	L
Water abstraction	Surface water abstraction	No
	Groundwater abstraction	No
Flow alteration	Discharge diversions and returns	H
	Interbasin flow transfer	M
	Hydrological regime modification including erosion due to increase in peak discharges	L
	Hydropeaking	L
	Flush flow	H
	Impoundment	H
Barriers/Connectivity	Artificial barriers upriver from the site	H
	Artificial barriers downriver from the site	M
Channelization	Channelisation / cross section alteration (e.g. deepening) including erosion due to this	L
	Sedimentation	No
Bank degradation	Bank degradation	L
Habitat degradation	Alteration of riparian vegetation	L
	Alteration of in-channels habitat	L
Others		

Problems and constraints for river restoration

Hydrology must be considered as the most important process because it affects the whole river system. Impoundment and water abstraction are relevant topics because of the dynamism of the hydropower sector and the need to mitigate and remediate adverse ecological impacts.

Hydrological measures focused on mitigating the flow alteration are often applied at a local/small scale without solving the hydrological dynamics that result from catchment-wide activities. Individual measures at each hydropower plant are usually set without considering the downstream or upstream situation.

Water abstraction due to hydropower production leads to residual water flow in the river channel, which can result in a completely dry riverbed at its maximum extent. Furthermore, water abstraction from rivers through inter-basin flow transfer schemes causes reduced flow of the donor river system.

Flush flow of water storage basins aiming to get rid of accumulated fine sediments, creates artificial flood events and affects the whole river system downstream of the dam.

In alpine regions, the continuity of small headwaters is often interrupted by blocking debris. As a consequence, sediment and wood are stored, causing a decrease of sediment and wood in downstream river sections and catchment-wide impacts on the ecosystems. The input of sediment at downstream reaches is a common but unsustainable countermeasure. Restoring natural processes (e.g. restoration of water and sediment regime by removing blocking debris in the upper catchment) has a better effect on recovery, compared to local scale interventions (e.g. wood or gravel addition at a lower part of the river catchment).

Large impoundments of storage power plants in the alpine region result in a reduction of the natural flow and a disruption of the sediment regime at a local scale. These impoundments also affect the downstream sections particularly with regard to altered water temperature or flow regime and/or decreased water quantity, depending on the operating method of the storage power plant.

Measures

Common restoration practice

Most of the measures taken in *small, single-thread highland rivers* aim to restore the flow alteration. Most important is the restoration of the natural flow regime, re-establishing natural flow dynamics and increasing water flow quantity in case of residual water flow.

Score per measure category/measure of relevance, effect in-channel, effect on the floodplain and costs the measure in comparison to other measures within this river type (No = no relevance or effect, L = low relevance or effect, M = moderate relevance or effect, H = high relevance or effect of the measure) and indication a prioritisation of measures (L = low priority, M = moderate priority, H = high priority).

Measure category	Measure	Relevance	Effect in-channel	Effect floodplain	Costs	Prioritisation
Decrease pollution	Decrease point source pollution	L	L	No	H	L
	Decrease diffuse pollution input	L	L	No	H	L
Water flow quantity	Reduce surface water abstraction	H	H	No	M	H
	Improve water retention	L	L	No	L	L
	Reduce groundwater abstraction	No				

Measure category	Measure	Relevance	Effect in-channel	Effect floodplain	Costs	Prioritisation
	Improve water storage	L	L	No	H	L
	Increase minimum flow	H	H	No	M	H
	Water diversion and transfer	H	H	No	M	H
	Recycle used water	No				
	Reduce water consumption	No				
Sediment quantity	Add/feed sediment	H	H	No	M	H
	Reduce undesired sediment input	L	L	No	H	L
	Prevent sediment accumulation	No				
	Improve continuity of sediment transport	H	H	No	M	H
	Trap sediments	No				
	Reduce impact of dredging	No				
Flow dynamics	Establish natural environmental flows	H	H	No	M	H
	Modify hydropeaking	L	L	No	M	H
	Increase flood frequency and duration	L	L	No	M	H
	Reduce anthropogenic flow peaks	L	L	No	M	H
	Shorten the length of impounded reaches	H	H	No	M	H
	Favour morphogenic flows	H	H	No	M	H
Longitudinal connectivity	Install fish pass, bypass, side channels	L	L	No	H	M
	Install facilities for downriver migration	L	L	No	H	L
	Manage sluice, weir, and turbine operation	H	H	No	M	H
	Remove barrier	H	H	No	H	H
	Modify or remove culverts, syphons, piped rivers	No				
In-channel habitat conditions	Remove bed fixation	L	L	No	L	L
	Remove bank fixation	L	L	No	L	L
	Remove sediment	L	L	No	L	L
	Add sediment (e.g. gravel)	L	L	No	L	L
	Manage aquatic vegetation	L	L	No	L	L
	Remove in-channel hydraulic structures	L	L	No	L	L
	Creating shallows near the bank	L	L	No	L	L
	Recruitment or placement of large wood	L	L	No	L	L
	Boulder placement	No				

Measure category	Measure	Relevance	Effect in-channel	Effect floodplain	Costs	Prioritisation
	Initiate natural channel dynamics	L	L	No	L	L
	Create artificial gravel bar or riffle	L	L	No	L	L
Riparian zone	Develop buffer strips to reduce nutrients	L	L	No	M	L
	Develop buffer strips to reduce fine sediments	No				
	Develop natural vegetation on buffer strips	No				
River planform	Re-meander water course	No				
	Widening or re-braiding of water course	No				
	Create a shallow water course	No				
	Narrow over-widened water course	No				
	Create low-flow channels	No				
	Allow/initiate lateral channel migration	No				
	Create secondary floodplain	No				
Floodplain	Reconnect backwaters, oxbow-lakes, wet-lands	No				
	Create backwaters, oxbow-lakes, wetlands	No				
	Lower embankments, levees or dikes	No				
	Replace embankments, levees or dikes	No				
	Remove embankments, levees or dikes	No				
	Remove vegetation	No				

Promising and new measures

Individual mitigation measures at each hydropower plant should be coordinated at a catchment scale. A master-plan at larger scale is necessary.

Large impoundments for hydropower production situated at highland rivers affect bed-load transport and create a sediment deficit in downstream sections. Flush flows of the water storage basins, aiming to get rid of accumulated fine sediments, create artificial flood events associated with high loads of suspended sediment and affect the river's bio-coenosis. Within the EU Interreg IIIB Project ALPRESERV a water resources management concept was developed based on an extensive ecological survey. The optimised flushing programme integrates demands of water management, hydropower production and ecology.

Water sections affected by residual water flow are restored by re-establishing a nature-like flow regime. The base flow will be increased and morphological improvements of key habitats could additionally mitigate the pressure.

Dam or weir removal is a promising measure in the alpine region to re-activate the stored sediment and to ensure a continuous sediment flow. Especially at the scale of the catchment such measures will produce strong effects. The river is not considered in isolation but is seen and dealt with as part of its catchment.


Figure: Sediment re-activation at a small highland river by dam removal, at a tributary to the river Lech in Tyrol, Austria (situation before/after dam removal – Photos: Ch.Moritz).

Table 3. Promising measures and respective scale. The higher the scale the more effective the measure.

<table>
<tr><td></td><td colspan="5">Ecological key factor</td></tr>
<tr><td>Scale</td><td>Temperature and light regime (System conditions)</td><td>Flow regime (Hydrology)</td><td>Profile variation, substrate heterogeneity and organic material (Morphology)</td><td>Oxygen regime, nutrient and toxic load (Chemistry)</td><td>Connectivity (Biology)</td></tr>
<tr><td>Catchment</td><td colspan="2">Ground water</td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td colspan="2">Surface water hydrology</td><td></td><td></td></tr>
<tr><td></td><td></td><td colspan="2">Sediment regime</td><td></td><td></td></tr>
<tr><td></td><td></td><td>Free flow</td><td></td><td colspan="2">Connectivity</td></tr>
<tr><td></td><td></td><td></td><td></td><td>Nutrients and organic load</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td>Toxicants</td><td></td></tr>
<tr><td>River stretch</td><td colspan="5">Riparian zone</td></tr>
<tr><td></td><td></td><td colspan="2">Profile</td><td></td><td></td></tr>
<tr><td></td><td></td><td colspan="2">Maintenance</td><td></td><td></td></tr>
<tr><td>Site</td><td></td><td colspan="2">Habitat</td><td></td><td></td></tr>
</table>

Especially in *small, single-thread highland rivers,* catchment wide measures and measures restoring the natural system conditions (processes that fit to the current climatological and geo-morphological conditions) are most effective (see table below).

Monitoring scheme

Monitoring schemes should follow some basic principles that apply to all river types:

- Biotic as well as abiotic variables should be monitored. The restoration measures might have succeeded to create the desired habitats but the effect on biota might be limited due to other pressures at larger scales which have not been addressed in the restoration project.
- In-channel, riparian, as well as floodplain conditions should be monitored. Besides the biological quality elements relevant for the Water Framework Directive, restoration can also have positive effects on other semi-aquatic and terrestrial organism groups, like ground beetles and floodplain vegetation. Indeed, there is empirical evidence that effects on other organism groups can be larger.
- Monitoring has to be conducted at appropriate spatial and temporal scales that reflect (i) the habitat needs of the organisms (e.g. monitoring microhabitat substrate patches for macroinvertebrates, mesohabitat features for fish), (ii) all life stages (e.g. monitoring in-channel and riparian habitats for macroinvertebrates with terrestrial life-stages), (iii) and the reproductive cycle as well as dispersal abilities (long-term monitoring to also cover effects of restoration on long-lived species and weak dispersers).
- Looking at the spatial and time scale of many current restoration measures macro-invertebrates are most suited for river monitoring. Fish population are strongly managed and reflect larger scale conditions, macrophytes bear a long history as they disappear only slowly and algae reflect to short time scales and very, very local conditions. Floodplains are large scaled and best be monitored by vegetation. Riparian zone can be monitored by using vegetation or carabid beetles.
- A Before-After-Control-Impact design should be applied to allow disentangling the effect of restoration from general trends in the whole river or catchment.
- However, the final selection of the organism groups, and spatial / temporal scales monitored strongly depends on the objectives and applied measures. Of course, it is reasonable to focus on the abiotic and biotic variables and scales that potentially have been affected by the restoration measures (e.g. in-channel habitat conditions by in-channel measures).
- Monitoring results should be used for adaptive management, i.e. to react on unanticipated effects and trends, and this should be included in the planning from the beginning ("Plan-B").

For further reading and practical guidelines we refer to the handbook of the River Restoration Centre (River Restoration Centre 2011).

The relevance of a variable at the scale of the river, riparian zone and floodplain scored in comparison to other variables within this river type (No = no relevance, L = low relevance, M = moderate relevance, H = high relevance)

Variable group	Variable	River	Riparian zone	Floodplain
River hydrology	Water quantity, Flow regime type, Average monthly flows	H	L	No
In-channel hydraulics	Baseflow index, Morphologically meaningful discharges	H	M	No
Floodplain morphology		No	No	No
In-channel morphology	Profile (longitudinal, transversal), sediment regime and budget,	H	M	No
	Meso-/micro-structures	H	L	No
Chemistry	Nutrients	L	L	No
	Toxicants	L	L	No
	Others			
	Water temperature	H	No	No
Biology	Algae	L	No	No
	Macrophytes	L	L	No
	Macroinvertebrates	H	H	No
	Fish	H	H	No
	Floodplain/riparian vegetation	L	L	No
	Terrestrial fauna	No	L	No

Fact sheet: Medium-large, sinuous-straight highland rivers with bedrock-coarse mixed sediments

General description

Valley- and planform	The valley form varies from a gorge to a V-shaped valley and the channel is mainly characterized by a straight planform.
Hydrology	These rivers are dominated by a discharge maximum at early summer (May, June) due to snow melt; except glacial rivers – see fact sheet 14
Morphology	The morphology of these river types varies according to the dominating bed material and the gradient. Streams with higher gradient are characterized by usually strongly confined and highly stable river beds because of the low erodibility of the bedrock bed and bank material. These, sediment supply-limited, single-thread channels exhibit no continuous alluvial bed, but some alluvial material may be stored in scour holes, or behind flow obstructions such as large boulders. Very coarse bed sediment and large wood pieces – delivered by debris falls, slides and flows – accumulate as colluvial valley fill to form the channel bed. Very low and variable fluvial transport limited by shallow flows. Small, relatively low gradient channels at the extremities of the stream network show mixed bed sediments delivered by less catastrophic hillslope processes than the steep subtype accumulate as colluvial valley fill to form the channel bed. Very low and variable fluvial transport limited by shallow flows. (REFORM D21 Type 1-3).
Chemistry	Depending on the geology, pH can vary from 7 to 8. The trophic level is oligotroph, the saprobic indices are between 1,00 and 1,75 (oligosaprob - β-mesosaprob). A distinction can be made between siliceous and calcareous rivers.
Riparian zone	Due to the narrow valley there is no floodplain developed. The river channel is accompanied mainly by bedrock bank or pioneer vegetation. The valley sides are dominated by typical montane tree species.

Photo: Medium-large, sinuous-straight highland river with bedrock-coarse mixed sediments in Austria (BOKU, IHG).

Pressures

Major pressures

The prevailing hydromorphological pressure in *medium-large, single-thread highland rivers* in the alpine region is flow alteration (impoundment, hydropeaking and/or discharge diversions) resulting from hydroelectric power production.

Score of pressure level imposed on medium-large, single-thread highland rivers categorised according to pressure category and pressure, respectively (score in comparison to other pressures within this river type: No = no pressure/stress, L = low pressure/stress, M = moderate pressure/stress, H = high pressure/stress).

Pressure category	**Pressure**	**Score**
Point sources	Point sources	L
Diffuse sources	Diffuse sources	L
Water abstraction	Surface water abstraction	No
	Groundwater abstraction	No
Flow alteration	Discharge diversions and returns	H
	Interbasin flow transfer	M
	Hydrological regime modification including erosion due to increase in peak discharges	M
	Hydropeaking	H
	Flush flow	H
	Impoundment	H
Barriers/Connectivity	Artificial barriers upriver from the site	H
	Artificial barriers downriver from the site	M
Channelization	Channelisation / cross section alteration (e.g. deepening) including erosion due to this	L
	Sedimentation	No
Bank degradation	Bank degradation	L
Habitat degradation	Alteration of riparian vegetation	L
	Alteration of in-channels habitat	L
Others		

Problems and constraints for river restoration

In alpine regions, the continuity of small headwaters is often interrupted by blocking debris. As a consequence, sediment and wood are stored, causing a decrease of sediment and wood in downstream river sections and catchment-wide impacts on the ecosystems.

Large impoundments of storage power plants in the alpine region result in a reduction of the natural flow and a disruption of the sediment regime at a local scale. These impoundments also affect the downstream sections particularly with regard to altered water temperature or flow regime and/or decreased water quantity, depending on the operating method of the storage power plant.

Hydropeaking impacts medium-large river sections through a high variation of artificial discharge changes with highly variable water levels within a day, due to the need to satisfy the temporally fluctuating demand of electric power (through storage and pump-storage hydropower plants). Biota is strongly affected by several artificial peaks per day through stranding and drifting.

Water abstraction due to hydropower production leads to residual water flow in the river channel, which can result in a completely dry riverbed at its maximum extent. Furthermore, water abstraction from rivers through inter-basin flow transfer schemes causes reduced flow of the donor river system.

Flush flow of water storage basins aiming to get rid of accumulated fine sediments, creates artificial flood events and affects the whole river system downstream of the dam.

Measures

Common restoration practice

Most of the measures taken in *medium-large, single-thread highland rivers* aim to restore the flow alteration.

Most important is the restoration of the natural flow regime, the re-establishment of the natural flow dynamics and the increase of water flow quantity in case of residual water flow. Furthermore, natural sediment regime and wood delivery must be restored. Sometimes, in-stream habitat restoration is performed to mitigate the negative effects of hydropeaking.

Score per measure category/measure of relevance, effect in-channel, effect on the floodplain and costs the measure in comparison to other measures within this river type (No = no relevance or effect, L = low relevance or effect, M = moderate relevance or effect, H = high relevance or effect of the measure) and indication a prioritisation of measures (L = low priority, M = moderate priority, H = high priority).

Measure category	Measure	Relevance	Effect in-channel	Effect floodplain	Costs	Prioritisation
Decrease pollution	Decrease point source pollution	L	L	No	H	L
	Decrease diffuse pollution input	L	L	No	H	L
Water flow quantity	Reduce surface water abstraction	H	H	No	M	H
	Improve water retention	L	L	No	L	L
	Reduce groundwater abstraction	No				
	Improve water storage	L	L	No	H	L
	Increase minimum flow	H	H	No	M	H
	Water diversion and transfer	H	H	No	M	H
	Recycle used water	No				
	Reduce water consumption	No				
Sediment quantity	Add/feed sediment	H	H	No	M	H

Measure category	Measure	Relevance	Effect in-channel	Effect floodplain	Costs	Prioritisation
	Reduce undesired sediment input	L	L	No	H	L
	Prevent sediment accumulation	No				
	Improve continuity of sediment transport	H	H	No	M	H
	Trap sediments	No				
	Reduce impact of dredging	No				
Flow dynamics	Establish natural environmental flows	H	H	No	M	H
	Modify hydropeaking	H	H	No	M	H
	Increase flood frequency and duration	H	H	No	M	H
	Reduce anthropogenic flow peaks	H	H	No	M	H
	Shorten the length of impounded reaches	H	H	No	M	H
	Favour morphogenic flows	H	H	No	M	H
Longitudinal connectivity	Install fish pass, bypass, side channels	H	H	No	H	M
	Install facilities for downriver migration	L	L	No	H	L
	Manage sluice, weir, and turbine operation	H	H	No	M	H
	Remove barrier	H	H	No	H	H
	Modify or remove culverts, syphons, piped rivers	No				
In-channel habitat conditions	Remove bed fixation	L	L	No	L	L
	Remove bank fixation	L	L	No	L	L
	Remove sediment	L	L	No	L	L
	Add sediment (e.g. gravel)	L	L	No	L	L
	Manage aquatic vegetation	L	L	No	L	L
	Remove in-channel hydraulic structures	L	L	No	L	L
	Creating shallows near the bank	M	M	No	M	M
	Recruitment or placement of large wood	M	M	No	M	M
	Boulder placement	No				
	Initiate natural channel dynamics	H	H	No	L	H
	Create artificial gravel bar or riffle	M	M	No	M	M
Riparian zone	Develop buffer strips to reduce nutrients	L	L	No	M	L
	Develop buffer strips to reduce fine sediments	No				
	Develop natural vegetation on buffer strips	No				
River planform	Re-meander water course	No				

Measure category	Measure	Relevance	Effect in-channel	Effect floodplain	Costs	Prioritisation
	Widening or re-braiding of water course	No				
	Create a shallow water course	No				
	Narrow over-widened water course	No				
	Create low-flow channels	No				
	Allow/initiate lateral channel migration	No				
	Create secondary floodplain	No				
Floodplain	Reconnect backwaters, oxbow-lakes, wetlands	No				
	Create backwaters, oxbow-lakes, wetlands	No				
	Lower embankments, levees or dikes	No				
	Replace embankments, levees or dikes	No				
	Remove embankments, levees or dikes	No				
	Remove vegetation	No				

Problems and constraints with common restoration practice

Hydrology must be considered as the most important process because it affects the whole river system.

Hydropeaking, impoundment and water abstraction are relevant topics because of the dynamism of the hydropower sector and the need to mitigate and remediate adverse ecological impacts.

Hydrological measures focused on mitigating the flow alteration are often applied at a local/small scale without solving the hydrological dynamics that result from catchment-wide activities. Individual measures at each hydropower plant are usually set without considering the downstream or upstream situation.

Considering the restoration of the sediment regime, the catchment scale approach is essential. Even though the sediment regime in highland river types is usually not compromised, the building of check dams and the subsequent retention of sediment and wood can cause negative effects. These effects (e.g. increased bed and bank erosion, bed incision, and negative sediment budget in wide floodplains) are visible far downstream at the lowland rivers. The input of sediment at downstream reaches is a common but unsustainable countermeasure. Restoring natural processes (e.g. restoration of water and sediment regime by removing blocking debris in the upper catchment) has a better effect on recovery, compared to local scale interventions (e.g. wood or gravel addition at a lower part of the river catchment).

Promising and new measures

Individual mitigation measures at each hydropower plant should be coordinated at a catchment scale. A master-plan at larger scale is necessary.

Dam or weir removal is a promising measure in the alpine region to re-activate the stored sediment and to ensure a continuous sediment flow. Especially, at the scale of the catchment such measures will sort strong effects. The river is not considered in solitude but is seen and dealt with as part of its catchment.

Large impoundments for hydropower production situated at highland rivers affect bed-load transport and create a sediment deficit in downstream sections. Flush flow of the water storage basins, aiming to get rid of accumulated fine sediments, creates artificial flood events associated with high loads of suspended sediment and affect the river's bio-coenosis. Within the EU Interreg IIIB Project ALPRESERV a water resources management concept was developed based on an extensive ecological survey. The optimised flushing programme integrates demands of water management, hydropower production and ecology.

The restitution of the peak flow directly into a lake, a compensation reservoir or into a parallel tailwater channel, and the controlled restitution of turbine water into the river in order to improve flow regime and re-establish natural-like condition are the most common measures.

Figure: The increase of base flow and the peak diversion into a compensation basin mitigated the effects of hydropeaking and water abstraction due to hydropower production at the Bregenzer Ach in Austria (BOKU,IHG)

Hydropeaking has a strong impact on aquatic fauna. Drift and stranding are the most important mechanisms. Morphological improvements of river sections, affected by hydropeaking, were set as promising new measure recently. Hereby, the restoration of river morphology has to focus on the development of keystone habitats, preferential for spawning and fry, and the improvement of existing habitats. First evaluations showed that the restoration of river morphology is only an additional tool to mitigate hydropeaking impacts. These measures will not be sufficient to fully mitigate strong hydropeaking effects that can only be done by the improvement of the flow regime such as slower changes in discharge variation or higher low flow level.

Another promising new measure is the building of multiple purpose reservoirs. These basins are located in wider valleys downstream and act as compensation basin to dampen the peak flow, provide additional flood protection, create aquatic/terrestrial biotopes and can be used for leisure activities by the local population.

Water sections affected by residual water flow are restored by re-establishing a nature-like flow regime. Increasing the base flow and morphologically improving the key habitats could additionally mitigate the pressure.

Especially, in *medium-large, single-thread highland rivers* catchment wide measures and measures restoring the natural system conditions (processes that fit to the current climatological and geo-morphological conditions) are most effective (see table below).

Table 3. Promising measures and respective scale. The higher the scale the more effective the measure.

	Ecological key factor				
Scale	Temperature and light regime (System conditions)	Flow regime (Hydrology)	Profile variation, substrate heterogeneity and organic material (Morphology)	Oxygen regime, nutrient and toxic load (Chemistry)	Connectivity (Biology)
Catchment	Ground water				
	Surface water hydrology				
	Sediment regime				
		Free flow	↔	Connectivity	
			Nutrients and organic load		
				Toxicants	
River stretch	Riparian zone				
		Profile			
		Maintenance			
Site		Habitat			

Monitoring scheme

Monitoring schemes should follow some basic principles that apply to all river types:

- Biotic as well as abiotic variables should be monitored. The restoration measures might have succeeded to create the desired habitats but the effect on biota might be limited due to other pressures at larger scales which have not been addressed in the restoration project.

- In-channel, riparian, as well as floodplain conditions should be monitored. Besides the biological quality elements relevant for the Water Framework Directive, restoration can also have positive effects on other semi-aquatic and terrestrial organism groups, like ground beetles and floodplain vegetation. Indeed, there is empirical evidence that effects on other organism groups can be larger.
- Monitoring has to be conducted at appropriate spatial and temporal scales that reflect (i) the habitat needs of the organisms (e.g. monitoring microhabitat substrate patches for macroinvertebrates, mesohabitat features for fish), (ii) all life stages (e.g. monitoring in-channel and riparian habitats for macroinvertebrates with terrestrial life-stages), (iii) and the reproductive cycle as well as dispersal abilities (long-term monitoring to also cover effects of restoration on long-lived species and weak dispersers).
- Looking at the spatial and time scale of many current restoration measures macro-invertebrates are most suited for river monitoring. Fish population are strongly managed and reflect larger scale conditions, macrophytes bear a long history as they disappear only slowly and algae reflect to short time scales and very, very local conditions. Floodplains are large scaled and best be monitored by vegetation. Riparian zone can be monitored by using vegetation or carabid beetles.
- A Before-After-Control-Impact design should be applied to allow disentangling the effect of restoration from general trends in the whole river or catchment.
- However, the final selection of the organism groups, and spatial / temporal scales monitored strongly depends on the objectives and applied measures. Of course, it is reasonable to focus on the abiotic and biotic variables and scales that potentially have been affected by the restoration measures (e.g. in-channel habitat conditions by in-channel measures).
- Monitoring results should be used for adaptive management, i.e. to react on unanticipated effects and trends, and this should be included in the planning from the beginning ("Plan-B").

For further reading and practical guidelines we refer to the handbook of the River Restoration Centre (River Restoration Centre 2011).

The relevance of a variable at the scale of the river, riparian zone and floodplain scored in comparison to other variables within this river type (No = no relevance, L = low relevance, M = moderate relevance, H = high relevance)

Variable group	**Variable**	**River**	**Riparian zone**	**Floodplain**
River hydrology	Water quantity, flow regime type, average monthly flows	H	L	No
In-channel hydraulics	Peak flow, baseflow index, Qmax/Qmin, hydropeak frequency, morphologically meaningful discharges	H	M	No
Floodplain morphology		No	No	No
In-channel morphology	Profile (longitudinal, transversal), sediment regime and budget,	H	M	No

Variable group	Variable	River	Riparian zone	Floodplain
	Meso-/micro-structures	H	L	No
Chemistry	Nutrients	L	L	No
	Toxicants	L	L	No
	Others			
	Water temperature	H	No	No
Biology	Algae	L	No	No
	Macrophytes	L	L	No
	Macroinvertebrates	H	H	No
	Fish	H	H	No
	Floodplain/riparian vegetation	L	L	No
	Terrestrial fauna	No	L	No

Fact sheet: Small, cascade, step-pool/plain bed, riffle-pool highland rivers with (very) coarse sediments

General description

Valley- and planform	The valley form varies from a gorge to a V-shaped valley and the single-thread channel is mainly characterized by a straight to sinuous planform.
Hydrology	These rivers are dominated by a discharge maximum at early summer (May, June) due to snow melt; except glacial rivers – see fact sheet 14
Morphology	The morphology of these river types varies according to the dominating bed material and the gradient. Very steep streams with coarse bed material consisting mainly of boulders and local exposures of bedrock that split the flow and allow throughput of bed material finer than the large clasts dominating the bed structure. Sequence of channel spanning accumulations of boulders and cobbles (steps) support broken, fast-flowing, turbulent, shallow flow threads, separated by pools that frequently span the channel, are usually lined with finer, cobble-sized, material, and support deeper, slower flowing water that is also often turbulent. If the gradient is getting lower, flows are fairly uniform, comprised of glides and runs with occasional rapids. Total sediment transport is low and is supplied mainly by bank erosion / failure and fluvial transport from upstream, but debris flows may occur in some locations. Coarse cobble-gravel sediments are sorted to reflect the flow pattern and bed morphology (REFORM D21 Typ 4-7).
Chemistry	Depending on the geology pH can vary from 7 to 8. The trophic level is oligotroph, the saprobic indices are between 1,00 and 1,75 (oligosaprob - β-mesosaprob). A distinction can be made between siliceous and calcareous rivers.
Riparian zone	Due to the narrow valley there is no floodplain developed. The river channel is accompanied mainly by bedrock banks or by pioneer vegetation. The valley sides are dominated by typical montane tree species. Above the tree line, alpine meadows, shrubs and sporadic dwarfed trees are predominant.

Photo: Small, cascade (left photo), step-pool/plain bed (right photo), riffle-pool highland rivers with (very) coarse sediments in Austria (BOKU, IHG).

Pressures

Major pressures

The prevailing hydromorphological pressure in *small, cascade, step-pool/plain bed, riffle-pool highland rivers* in the alpine region is flow alteration (impoundment and/or discharge diversions) resulting from hydroelectric power production.

In some cases, large storage basins are fed through major water transfer from other catchments.

Score of pressure level imposed on small, cascade, step-pool/plain bed, riffle-pool highland rivers categorised according to pressure category and pressure, respectively (score in comparison to other pressures within this river type: No = no pressure/stress, L = low pressure/stress, M = moderate pressure/stress, H = high pressure/stress).

Pressure category	**Pressure**	**Score**
Point sources	Point sources	L
Diffuse sources	Diffuse sources	L
Water abstraction	Surface water abstraction	No
	Groundwater abstraction	No
Flow alteration	Discharge diversions and returns	H
	Interbasin flow transfer	M
	Hydrological regime modification including erosion due to increase in peak discharges	L
	Hydropeaking	L
	Flush flow	H
	Impoundment	H
Barriers/Connectivity	Artificial barriers upriver from the site	H
	Artificial barriers downriver from the site	M
Channelization	Channelisation / cross section alteration (e.g. deepening) including erosion due to this	L
	Sedimentation	No
Bank degradation	Bank degradation	L
Habitat degradation	Alteration of riparian vegetation	L
	Alteration of in-channels habitat	L
Others		

Problems and constraints for river restoration

Hydrology must be considered as the most important process because it affects the whole river system.

Impoundment and water abstraction are relevant topics because of the dynamism of the hydropower sector and the need to mitigate and remediate adverse ecological impacts.

Hydrological measures focused on mitigating the flow alteration are often applied at a local/small scale without solving the hydrological dynamics that result from catchment-wide activities. Individual measures at each hydropower plant are usually set without considering the downstream or upstream situation.

Water abstraction due to hydropower production leads to residual water flow in the river channel, which can result in a completely dry riverbed at its maximum extent. Furthermore, water abstraction from rivers through inter-basin flow transfer schemes causes reduced flow of the donor river system.

Flush flow of water storage basins aiming to get rid of accumulated fine sediments, creates artificial flood events and affects the whole river system downstream of the dam.

In alpine regions, the continuity of small headwaters is often interrupted by blocking debris. As a consequence, sediment and wood are stored, causing a decrease of sediment and wood in downstream river sections and catchment-wide impacts on the ecosystems. The input of sediment at downstream reaches is a common but unsustainable countermeasure. Restoring natural processes (e.g. restoration of water and sediment regime by removing blocking debris in the upper catchment) has a better effect on recovery, compared to local scale interventions (e.g. wood or gravel addition at a lower part of the river catchment).

Large impoundments of storage power plants in the alpine region result in a reduction of the natural flow and a disruption of the sediment regime at a local scale. These impoundments also affect the downstream sections particularly with regard to altered water temperature or flow regime and/or decreased water quantity, depending on the operating method of the storage power plant.

Measures

Common restoration practice

Most of the measures taken in *small, cascade, step-pool/plain bed, riffle-pool highland rivers* aim to restore the flow alteration. Most important is the restoration of the natural flow regime, the re-establishment of the natural flow dynamics and the increase of water flow quantity in case of residual water flow. Furthermore, natural sediment regime and wood delivery must be restored.

Score per measure category/measure of relevance, effect in-channel, effect on the floodplain and costs the measure in comparison to other measures within this river type (No = no relevance or effect, L = low relevance or effect, M = moderate relevance or effect, H = high relevance or effect of the measure) and indication a prioritisation of measures (L = low priority, M = moderate priority, H = high priority).

Measure category	Measure	Relevance	Effect in-channel	Effect floodplain	Costs	Prioritisation
Decrease pollution	Decrease point source pollution	L	L	No	H	L
	Decrease diffuse pollution input	L	L	No	H	L
Water flow quantity	Reduce surface water abstraction	H	H	No	M	H
	Improve water retention	L	L	No	L	L
	Reduce groundwater abstraction	No				

REFORM
REstoring rivers FOR effective catchment Management

Measure category	Measure	Relevance	Effect in-channel	Effect floodplain	Costs	Prioritisation
	Improve water storage	L	L	No	H	L
	Increase minimum flow	H	H	No	M	H
	Water diversion and transfer	H	H	No	M	H
	Recycle used water	No				
	Reduce water consumption	No				
Sediment quantity	Add/feed sediment	H	H	No	M	H
	Reduce undesired sediment input	L	L	No	H	L
	Prevent sediment accumulation	No				
	Improve continuity of sediment transport	H	H	No	M	H
	Trap sediments	No				
	Reduce impact of dredging	No				
Flow dynamics	Establish natural environmental flows	H	H	No	M	H
	Modify hydropeaking	L	L	No	M	H
	Increase flood frequency and duration	L	L	No	M	H
	Reduce anthropogenic flow peaks	L	L	No	M	H
	Shorten the length of impounded reaches	H	H	No	M	H
	Favour morphogenic flows	H	H	No	M	H
Longitudinal connectivity	Install fish pass, bypass, side channels	L	L	No	H	M
	Install facilities for downriver migration	L	L	No	H	L
	Manage sluice, weir, and turbine operation	H	H	No	M	H
	Remove barrier	H	H	No	H	H
	Modify or remove culverts, syphons, piped rivers	No				
In-channel habitat conditions	Remove bed fixation	L	L	No	L	L
	Remove bank fixation	L	L	No	L	L
	Remove sediment	L	L	No	L	L
	Add sediment (e.g. gravel)	L	L	No	L	L
	Manage aquatic vegetation	L	L	No	L	L
	Remove in-channel hydraulic structures	L	L	No	L	L
	Creating shallows near the bank	L	L	No	L	L
	Recruitment or placement of large wood	L	L	No	L	L
	Boulder placement	No				

Measure category	Measure	Relevance	Effect in-channel	Effect floodplain	Costs	Prioritisation
	Initiate natural channel dynamics	L	L	No	L	L
	Create artificial gravel bar or riffle	L	L	No	L	L
Riparian zone	Develop buffer strips to reduce nutrients	L	L	No	M	L
	Develop buffer strips to reduce fine sediments	No				
	Develop natural vegetation on buffer strips	No				
River planform	Re-meander water course	No				
	Widening or re-braiding of water course	No				
	Create a shallow water course	No				
	Narrow over-widened water course	No				
	Create low-flow channels	No				
	Allow/initiate lateral channel migration	No				
	Create secondary floodplain	No				
Floodplain	Reconnect backwaters, oxbow-lakes, wet-lands	No				
	Create backwaters, oxbow-lakes, wetlands	No				
	Lower embankments, levees or dikes	No				
	Replace embankments, levees or dikes	No				
	Remove embankments, levees or dikes	No				
	Remove vegetation	No				

Problems and constraints with common restoration practice

Hydrology must be considered as the most important process because it affects the whole river system.

Impoundment and water abstraction are relevant topics because of the dynamism of the hydropower sector and the need to mitigate and remediate adverse ecological impacts.

Hydrological measures focused on mitigating the flow alteration are often applied at a local/small scale without solving the hydrological dynamics that result from catchment-wide activities. Individual measures at each hydropower plant are usually set without considering the downstream or upstream situation.

Considering the restoration of the sediment regime, the catchment scale approach is essential. Even though the sediment regime in highland river types is usually not compromised, the building of check dams and the subsequent retention of sediment and wood can cause negative effects. These effects (e.g. increased bed and bank erosion, bed incision, and negative sediment budget in wide floodplains) are visible far downstream at the lowland rivers. The input of sediment at downstream reaches is a common but unsustainable countermeasure. Restoring natural processes (e.g. restoration of water and sediment regime by removing blocking debris in the upper catchment) has a better effect on recovery, compared to local scale interventions (e.g. wood or gravel addition at a lower part of the river catchment).

Promising and new measures

Individual mitigation measures at each hydropower plant should be coordinated at a catchment scale. A master-plan at larger scale is necessary.

Large impoundments for hydropower production situated at highland rivers affect bedload transport and create a sediment deficit in downstream sections. Flush flows of the water storage basins, aiming to get rid of accumulated fine sediments, create artificial flood events associated with high loads of suspended sediment and affect the river's biocoenosis. Within the EU Interreg IIIB Project ALPRESERV a water resources management concept was developed based on an extensive ecological survey. The optimised flushing programme integrates demands of water management, hydropower production and ecology.

Water sections affected by residual water flow are restored by re-establishing a nature-like flow regime. The base flow will be increased and morphological improvements of key habitats could additionally mitigate the pressure.

Dam or weir removal is a promising measure in the alpine region to re-activate the stored sediment and to ensure a continuous sediment flow. Especially at the scale of the catchment such measures will produce strong effects. The river is not considered in isolation but is seen and dealt with as part of its catchment.

Figure: Sediment re-activation at a small highland river by dam removal, at a tributary to the river Lech in Tyrol, Austria (situation before/after dam removal – Photos: Ch.Moritz).

Especially, in *small, cascade, step-pool/plain bed, riffle-pool highland rivers* catchment wide measures and measures restoring the natural system conditions (processes that fit to the current climatological and geo-morphological conditions) are most effective (see table below).

Table 3. Promising measures and respective scale. The higher the scale the more effective the measure.

<table>
<tr><td></td><td colspan="5">Ecological key factor</td></tr>
<tr><td>Scale</td><td>Temperature and light regime (System conditions)</td><td>Flow regime (Hydrology)</td><td>Profile variation, substrate heterogeneity and organic material (Morphology)</td><td>Oxygen regime, nutrient and toxic load (Chemistry)</td><td>Connectivity (Biology)</td></tr>
<tr><td>Catchment</td><td colspan="2">Ground water</td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td colspan="2">Surface water hydrology</td><td></td><td></td></tr>
<tr><td></td><td></td><td colspan="2">Sediment regime</td><td></td><td></td></tr>
<tr><td></td><td></td><td>Free flow</td><td>↔</td><td colspan="2">Connectivity</td></tr>
<tr><td></td><td></td><td></td><td></td><td>Nutrients and organic load</td><td></td></tr>
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<tr><td>River stretch</td><td colspan="5">Riparian zone</td></tr>
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<tr><td></td><td></td><td colspan="2">Maintenance</td><td></td><td></td></tr>
<tr><td>Site</td><td></td><td colspan="2">Habitat</td><td></td><td></td></tr>
</table>

Monitoring scheme

Monitoring schemes should follow some basic principles that apply to all river types:

- Biotic as well as abiotic variables should be monitored. The restoration measures might have succeeded to create the desired habitats but the effect on biota might be limited due to other pressures at larger scales which have not been addressed in the restoration project.
- In-channel, riparian, as well as floodplain conditions should be monitored. Besides the biological quality elements relevant for the Water Framework Directive, restoration can also have positive effects on other semi-aquatic and terrestrial organism groups, like ground beetles and floodplain vegetation. Indeed, there is empirical evidence that effects on other organism groups can be larger.
- Monitoring has to be conducted at appropriate spatial and temporal scales that reflect (i) the habitat needs of the organisms (e.g. monitoring microhabitat substrate patches for macroinvertebrates, mesohabitat features for fish), (ii) all life stages (e.g. monitoring in-channel and riparian habitats for macroinvertebrates with terrestrial life-stages), (iii) and the reproductive cycle as well as dispersal

abilities (long-term monitoring to also cover effects of restoration on long-lived species and weak dispersers).

- Looking at the spatial and time scale of many current restoration measures macro-invertebrates are most suited for river monitoring. Fish population are strongly managed and reflect larger scale conditions, macrophytes bear a long history as they disappear only slowly and algae reflect to short time scales and very, very local conditions. Floodplains are large scaled and best be monitored by vegetation. Riparian zone can be monitored by using vegetation or carabid beetles.
- A Before-After-Control-Impact design should be applied to allow disentangling the effect of restoration from general trends in the whole river or catchment.
- However, the final selection of the organism groups, and spatial / temporal scales monitored strongly depends on the objectives and applied measures. Of course, it is reasonable to focus on the abiotic and biotic variables and scales that potentially have been affected by the restoration measures (e.g. in-channel habitat conditions by in-channel measures).
- Monitoring results should be used for adaptive management, i.e. to react on unanticipated effects and trends, and this should be included in the planning from the beginning ("Plan-B").

For further reading and practical guidelines we refer to the handbook of the River Restoration Centre (River Restoration Centre 2011).

The relevance of a variable at the scale of the river, riparian zone and floodplain scored in comparison to other variables within this river type (No = no relevance, L = low relevance, M = moderate relevance, H = high relevance)

Variable group	Variable	River	Riparian zone	Floodplain
River hydrology	Water quantity, Flow regime type, Average monthly flows	H	L	No
In-channel hydraulics	Baseflow index, Morphologically meaningful discharges	H	M	No
Floodplain morphology		No	No	No
In-channel morphology	Profile (longitudinal, transversal), sediment regime and budget,	H	M	No
	Meso-/micro-structures	H	L	No
Chemistry	Nutrients	L	L	No
	Toxicants	L	L	No
	Others			
	Water temperature	H	No	No
Biology	Algae	L	No	No
	Macrophytes	L	L	No
	Macroinvertebrates	H	H	No
	Fish	H	H	No

Variable group	Variable	River	Riparian zone	Floodplain
	Floodplain/riparian vegetation	L	L	No
	Terrestrial fauna	No	L	No

Fact sheet: Medium-large, cascade, step-pool/plain bed, riffle-pool, highland rivers with (very) coarse sediments

General description

Valley- and planform	The valley form varies from a gorge to a V-shaped valley and the single-thread channel is mainly characterized by a straight to sinuous planform.
Hydrology	These rivers are dominated by a discharge maximum at early summer (May, June) due to snow melt; except glacial rivers – see fact sheet 14
Morphology	The morphology of these river types varies according to the dominating bed material and the gradient. Very steep streams with coarse bed material consisting mainly of boulders and local exposures of bedrock that split the flow and allow throughput of bed material finer than the large clasts dominating the bed structure. Sequence of channel spanning accumulations of boulders and cobbles (steps) support broken, fast-flowing, turbulent, shallow flow threads, separated by pools that frequently span the channel and are usually lined with finer, cobble-sized material, and support deeper, slower flowing water that is also often turbulent. If the gradient is getting lower, flows are fairly uniform, comprised of glides and runs with occasional rapids. Total sediment transport is low and is supplied mainly by bank erosion / failure and fluvial transport from upstream, but debris flows may occur in some locations. Coarse cobble-gravel sediments are sorted to reflect the flow pattern and bed morphology (REFORM D21 Typ 4-7).
Chemistry	Depending on the geology pH can vary from 7 to 8. The trophic level is oligotroph, the saprobic indices are between 1,00 and 1,75 (oligosaprob - β-mesosaprob). A distinction can be made between siliceous and calcareous rivers.
Riparian zone	Due to the narrow valley there is no floodplain developed. The river channel is accompanied mainly by bedrock banks or by pioneer vegetation. The valley sides are dominated by typical montane tree species.

Photo: Medium-large, cascade, step-pool/plain bed, riffle-pool, highland rivers with (very) coarse sediments in Austria (BOKU, IHG).

Pressures

Major pressures

The prevailing hydromorphological pressure in *medium-large, cascade, step-pool/plain bed, riffle-pool, highland rivers* in the alpine region is flow alteration (impoundment, hydropeaking and/or discharge diversions) resulting from hydroelectric power production.

Score of pressure level imposed on small, cascade, step-pool/plain bed, riffle-pool, highland rivers categorised according to pressure category and pressure, respectively (score in comparison to other pressures within this river type: No = no pressure/stress, L = low pressure/stress, M = moderate pressure/stress, H = high pressure/stress).

Pressure category	**Pressure**	**Score**
Point sources	Point sources	L
Diffuse sources	Diffuse sources	L
Water abstraction	Surface water abstraction	No
	Groundwater abstraction	No
Flow alteration	Discharge diversions and returns	H
	Interbasin flow transfer	M
	Hydrological regime modification including erosion due to increase in peak discharges	M
	Hydropeaking	H
	Flush flow	H
	Impoundment	H
Barriers/Connectivity	Artificial barriers upriver from the site	H
	Artificial barriers downriver from the site	M
Channelization	Channelisation / cross section alteration (e.g. deepening) including erosion due to this	L
	Sedimentation	No
Bank degradation	Bank degradation	L
Habitat degradation	Alteration of riparian vegetation	L
	Alteration of in-channels habitat	L
Others		

Problems and constraints for river restoration

In alpine regions, the continuity of small headwaters is often interrupted by blocking debris. As a consequence, sediment and wood are stored, causing a decrease of sediment and wood in downstream river sections and catchment-wide impacts on the ecosystems.

Large impoundments of storage power plants in the alpine region result in a reduction of the natural flow and a disruption of the sediment regime at a local scale. These impoundments also affect the downstream sections particularly with regard to altered water temperature or flow regime and/or decreased water quantity, depending on the operating method of the storage power plant.

Hydropeaking impacts medium-large river sections through a high variation of artificial discharge changes with highly variable water levels within a day, due to the need to satisfy the temporally fluctuating demand of electric power (through storage and pump-storage hydropower plants). Biota is strongly affected by several artificial peaks per day through stranding and drifting.

Water abstraction due to hydropower production leads to residual water flow in the river channel, which can result in a completely dry riverbed at its maximum extent. Furthermore, water abstraction from rivers through inter-basin flow transfer schemes causes reduced flow of the donor river system.

Flush flow of water storage basins aiming to get rid of accumulated fine sediments, creates artificial flood events and affects the whole river system downstream of the dam.

Measures

Common restoration practice

Most of the measures taken in *medium-large, cascade, step-pool/plain bed, riffle-pool, highland rivers with (very) coarse sediments* aim to restore the flow alteration.

Most important is the restoration of the natural flow regime, the re-establishment of the natural flow dynamics and the increase of water flow quantity in case of residual water flow. Furthermore, natural sediment regime and wood delivery must be restored. Sometimes, in-stream habitat restoration is performed to mitigate the negative effects of hydropeaking.

Score per measure category/measure of relevance, effect in-channel, effect on the floodplain and costs the measure in comparison to other measures within this river type (No = no relevance or effect, L = low relevance or effect, M = moderate relevance or effect, H = high relevance or effect of the measure) and indication a prioritisation of measures (L = low priority, M = moderate priority, H = high priority).

Measure category	Measure	Relevance	Effect in-channel	Effect floodplain	Costs	Prioritisation
Decrease pollution	Decrease point source pollution	L	L	No	H	L
	Decrease diffuse pollution input	L	L	No	H	L
Water flow quantity	Reduce surface water abstraction	H	H	No	M	H
	Improve water retention	L	L	No	L	L
	Reduce groundwater abstraction	No				
	Improve water storage	L	L	No	H	L
	Increase minimum flow	H	H	No	M	H
	Water diversion and transfer	H	H	No	M	H
	Recycle used water	No				
	Reduce water consumption	No				
Sediment quantity	Add/feed sediment	H	H	No	M	H
	Reduce undesired sediment input	L	L	No	H	L

Measure category	Measure	Relevance	Effect in-channel	Effect floodplain	Costs	Prioritisation
	Prevent sediment accumulation	No				
	Improve continuity of sediment transport	H	H	No	M	H
	Trap sediments	No				
	Reduce impact of dredging	No				
Flow dynamics	Establish natural environmental flows	H	H	No	M	H
	Modify hydropeaking	H	H	No	M	H
	Increase flood frequency and duration	H	H	No	M	H
	Reduce anthropogenic flow peaks	H	H	No	M	H
	Shorten the length of impounded reaches	H	H	No	M	H
	Favour morphogenic flows	H	H	No	M	H
Longitudinal connectivity	Install fish pass, bypass, side channels	H	H	No	H	M
	Install facilities for downriver migration	L	L	No	H	L
	Manage sluice, weir, and turbine operation	H	H	No	M	H
	Remove barrier	H	H	No	H	H
	Modify or remove culverts, syphons, piped rivers	No				
In-channel habitat conditions	Remove bed fixation	L	L	No	L	L
	Remove bank fixation	L	L	No	L	L
	Remove sediment	L	L	No	L	L
	Add sediment (e.g. gravel)	L	L	No	L	L
	Manage aquatic vegetation	L	L	No	L	L
	Remove in-channel hydraulic structures	L	L	No	L	L
	Creating shallows near the bank	M	M	No	M	M
	Recruitment or placement of large wood	M	M	No	M	M
	Boulder placement	No				
	Initiate natural channel dynamics	H	H	No	L	H
	Create artificial gravel bar or riffle	M	M	No	M	M
Riparian zone	Develop buffer strips to reduce nutrients	L	L	No	M	L
	Develop buffer strips to reduce fine sediments	No				
	Develop natural vegetation on buffer strips	No				
River planform	Re-meander water course	No				
	Widening or re-braiding of water course	No				

Measure category	Measure	Relevance	Effect in-channel	Effect floodplain	Costs	Prioritisation
	Create a shallow water course	No				
	Narrow over-widened water course	No				
	Create low-flow channels	No				
	Allow/initiate lateral channel migration	No				
	Create secondary floodplain	No				
Floodplain	Reconnect backwaters, oxbow-lakes, wet-lands	No				
	Create backwaters, oxbow-lakes, wetlands	No				
	Lower embankments, levees or dikes	No				
	Replace embankments, levees or dikes	No				
	Remove embankments, levees or dikes	No				
	Remove vegetation	No				

Problems and constraints with common restoration practice

Hydrology must be considered as the most important process because it affects the whole river system.

Hydropeaking, impoundment and water abstraction are relevant topics because of the dynamism of the hydropower sector and the need to mitigate and remediate adverse ecological impacts.

Hydrological measures focused on mitigating the flow alteration are often applied at a local/small scale without solving the hydrological dynamics that result from catchment-wide activities. Individual measures at each hydropower plant are usually set without considering the downstream or upstream situation.

Considering the restoration of the sediment regime, the catchment scale approach is essential. Even though the sediment regime in highland river types is usually not compromised, the building of check dams and the subsequent retention of sediment and wood can cause negative effects. These effects (e.g. increased bed and bank erosion, bed incision, and negative sediment budget in wide floodplains) are visible far downstream at the lowland rivers. The input of sediment at downstream reaches is a common but unsustainable countermeasure. Restoring natural processes (e.g. restoration of water and sediment regime by removing blocking debris in the upper catchment) has a better effect on recovery, compared to local scale interventions (e.g. wood or gravel addition at a lower part of the river catchment).

Promising and new measures

Individual mitigation measures at each hydropower plant should be coordinated at a catchment scale. A master-plan at larger scale is necessary.

Dam or weir removal is a promising measure in the alpine region to re-activate the stored sediment and to ensure a continuous sediment flow. Especially, at the scale of the catchment such measures will sort strong effects. The river is not considered in solitude but is seen and dealt with as part of its catchment.

The restitution of the peak flow directly into a lake, a compensation reservoir or into a parallel tailwater channel, and the controlled restitution of turbine water into the river in order to improve flow regime and re-establish natural-like condition are the most common measures.

Hydropeaking has a strong impact on aquatic fauna. Drift and stranding are the most important mechanisms. Morphological improvements of river sections, affected by hydropeaking, were set as promising new measure recently. Hereby, the restoration of river morphology has to focus on the development of keystone habitats, preferential for spawning and fry, and the improvement of existing habitats. First evaluations showed that the restoration of river morphology is only an additional tool to mitigate hydropeaking impacts. These measures will not be sufficient to fully mitigate strong hydropeaking effects that can only be done by the improvement of the flow regime such as slower changes in discharge variation or higher low flow level.

Another promising new measure is the building of multiple purpose reservoirs. These basins are located in wider valleys downstream and act as compensation basin to dampen the peak flow, provide additional flood protection, create aquatic/terrestrial biotopes and can be used for leisure activities by the local population.

	Year 0	Year 1	Year 2	Year 3	Year 4+
Flush event	Flush	Short time slot for			Extended time slot for
Spring (April-May)		--	>80/130 m^3/s	>80/130 m^3/s	>90/160 m^3/s
Early summer (June-July)		--	--	--	>90/160 m^3/s
Late summer (Aug.-Sep.)		>80/130 m^3/s	>80/130 m^3/s	>90/160 m^3/s	>90/160 m^3/s
		Perennial flush at flood event (starting from HQ 5 peak – 130/300 m^3/s)			

Figure: Optimized flushing scheme of the hydropower plant Bodendorf at the river Mur in Styria, Austria. Result of the EU Interreg IIIB Project ALPRESERV.

Water sections affected by residual water flow are restored by re-establishing a nature-like flow regime. Increasing the base flow and morphologically improving the key habitats could additionally mitigate the pressure.

Large impoundments situated at highland rivers affect bedload transport of the rivers and create a sediment deficit in downstream sections. Flush flow of the water storage basins, aiming to get rid of accumulated fine sediments, creates artificial flood events associated with high loads of suspended sediment and affect the river's biocoenosis. Within the EU Interreg IIIB Project ALPRESERV a water resources management concept was developed based on an extensive ecological survey. The optimised flushing programme integrates demands of water management, hydropower production and ecology.

Especially, in *medium-large, cascade, step-pool/plain bed, riffle-pool, highland rivers with (very) coarse sediments* catchment wide measures and measures restoring the natural system conditions (processes that fit to the current climatological and geomorphological conditions) are most effective (see table below).

Table 3. Promising measures and respective scale. The higher the scale the more effective the measure.

	Ecological key factor				
Scale	Temperature and light regime (System conditions)	Flow regime (Hydrology)	Profile variation, substrate heterogeneity and organic material (Morphology)	Oxygen regime, nutrient and toxic load (Chemistry)	Connectivity (Biology)
Catchment ↓	Ground water				
	Surface water hydrology				
	Sediment regime				
		Free flow	↔	Connectivity	
			Nutrients and organic load		
				Toxicants	
River stretch	Riparian zone				
		Profile			
		Maintenance			
Site		Habitat			

Monitoring scheme

Monitoring schemes should follow some basic principles that apply to all river types:

- Biotic as well as abiotic variables should be monitored. The restoration measures might have succeeded to create the desired habitats but the effect on biota might be limited due to other pressures at larger scales which have not been addressed in the restoration project.
- In-channel, riparian, as well as floodplain conditions should be monitored. Besides the biological quality elements relevant for the Water Framework Directive, restoration can also have positive effects on other semi-aquatic and terrestrial organism groups, like ground beetles and floodplain vegetation. Indeed, there is empirical evidence that effects on other organism groups can be larger.
- Monitoring has to be conducted at appropriate spatial and temporal scales that reflect (i) the habitat needs of the organisms (e.g. monitoring microhabitat substrate patches for macroinvertebrates, mesohabitat features for fish), (ii) all life stages (e.g. monitoring in-channel and riparian habitats for macroinvertebrates with terrestrial life-stages), (iii) and the reproductive cycle as well as dispersal abilities (long-term monitoring to also cover effects of restoration on long-lived species and weak dispersers).
- Looking at the spatial and time scale of many current restoration measures macro-invertebrates are most suited for river monitoring. Fish population are strongly managed and reflect larger scale conditions, macrophytes bear a long history as they disappear only slowly and algae reflect to short time scales and very, very local conditions. Floodplains are large scaled and best be monitored by vegetation. Riparian zone can be monitored by using vegetation or carabid beetles.
- A Before-After-Control-Impact design should be applied to allow disentangling the effect of restoration from general trends in the whole river or catchment.
- However, the final selection of the organism groups, and spatial / temporal scales monitored strongly depends on the objectives and applied measures. Of course, it is reasonable to focus on the abiotic and biotic variables and scales that potentially have been affected by the restoration measures (e.g. in-channel habitat conditions by in-channel measures).
- Monitoring results should be used for adaptive management, i.e. to react on unanticipated effects and trends, and this should be included in the planning from the beginning ("Plan-B").

For further reading and practical guidelines we refer to the handbook of the River Restoration Centre (River Restoration Centre 2011).

The relevance of a variable at the scale of the river, riparian zone and floodplain scored in comparison to other variables within this river type (No = no relevance, L = low relevance, M = moderate relevance, H = high relevance)

Variable group	Variable	River	Riparian zone	Floodplain
River hydrology	Water quantity, flow regime type, average monthly flows	H	L	No
In-channel hydraulics	Peak flow, baseflow index, Qmax/Qmin, hydropeak frequency, morphologically meaningful discharges	H	M	No
Floodplain morphology		No	No	No
In-channel morphology	Profile (longitudinal, transversal), sediment regime and budget,	H	M	No
	Meso-/micro-structures	H	L	No
Chemistry	Nutrients	L	L	No
	Toxicants	L	L	No
	Others			
	Water temperature	H	No	No
Biology	Algae	L	No	No
	Macrophytes	L	L	No
	Macroinvertebrates	H	H	No
	Fish	H	H	No
	Floodplain/riparian vegetation	L	L	No
	Terrestrial fauna	No	L	No

Fact sheet: Glacial rivers (all Europe)

General description

Valley- and planform	The valley form varies from a gorge to a V-shaped valley and the single-thread channel is mainly characterized by a straight to sinuous planform.
Hydrology	These rivers are dominated by a discharge maximum at summer (July, August) due to glacial meltwater and by a discharge minimum in winter.
Morphology	The morphology of these river types varies according to the dominating bed material and the gradient. Streams with high gradient, strongly confined and highly stable river beds (because of the low erodibility of the bedrock bed and bank material), exhibit no continuous alluvial bed, but some alluvial material may be stored in scour holes, or behind flow obstructions such as large boulders. Very coarse bed sediment and large wood pieces delivered by debris falls, slides and flows accumulate as colluvial valley fill to form the channel bed. Very low and variable fluvial transport limited by shallow flows. Small, relatively low gradient channels at the extremities of the stream network show mixed bed sediments delivered by less catastrophic hillslope processes than the steep subtype accumulate as colluvial valley fill to form the channel bed. Very low and variable fluvial transport limited by shallow flows. (REFORM D21 Type 1-3). Very steep streams with coarse bed material consisting mainly of boulders and local exposures of bedrock that split the flow and allow throughput of bed material finer than the large clasts dominating the bed structure. Sequence of channel spanning accumulations of boulders and cobbles (steps) support broken, fast-flowing, turbulent, shallow flow threads, separated by pools that frequently span the channel, are usually lined with finer, cobble-sized, material, and support deeper, slower flowing water that is also often turbulent. If the gradient is getting lower, flows are fairly uniform, comprised of glides and runs with occasional rapids. Total sediment transport is low and is supplied mainly by bank erosion / failure and fluvial transport from upstream, but debris flows may occur in some locations. Coarse cobble-gravel sediments are sorted to reflect the flow pattern and bed morphology (REFORM D21 Typ 4-7). Typically during warm periods, a high proportion of fine sediments, coming from the glacial moraines, causes a high turbidity of the water.
Chemistry	Depending on the geology, pH can vary from 7 to 8. The trophic level is oligotroph, the saprobic indices are between 1,00 and 1,25 (oligosaprob). A distinction can be made between siliceous and calcareous rivers.
Riparian zone	Due to the narrow valley there is no floodplain developed. The river channel is accompanied by bedrock bank or pioneer vegetation. The valley sides are dominated by typical montane tree species. Above the tree line, alpine meadows, shrubs and sporadic dwarfed trees are predominant.

Photo: Glacial stream in Austria (BOKU, IHG).

Pressures

Major pressures

The prevailing hydromorphological pressure in glacial streams in the alpine region is flow alteration (impoundment, and/or discharge diversions) resulting from hydroelectric power production.

In some cases, large storage basins are fed through major water transfer from other catchments. This interbasin water transfer can alter the glacial flow regime to a snow melt dominated regime.

Larger glacial rivers can additionally be affected by hydropeaking or local morphological alteration.

Glacial river ecosystems support a unique flora and fauna, including endemic and threatened species which are adapted to harsh environmental conditions. Beside hydromporphological pressures, these ecosystems are under major pressure from climate change by retreating glaciers and shrinking snow cover.

Score of pressure level imposed on small, single-thread, lowland rivers categorised according to pressure category and pressure, respectively (score in comparison to other pressures within this river type: No = no pressure/stress, L = low pressure/stress, M = moderate pressure/stress, H = high pressure/stress).

Pressure category	**Pressure**	**Score**
Point sources	Point sources	L
Diffuse sources	Diffuse sources	L
Water abstraction	Surface water abstraction	No
	Groundwater abstraction	No
Flow alteration	Discharge diversions and returns	H

Pressure category	Pressure	Score
	Interbasin flow transfer	H
	Hydrological regime modification including erosion due to increase in peak discharges	L
	Hydropeaking	M
	Flush flow	H
	Impoundment	H
Barriers/Connectivity	Artificial barriers upriver from the site	H
	Artificial barriers downriver from the site	M
Channelization	Channelisation / cross section alteration (e.g. deepening) including erosion due to this	M
	Sedimentation	No
Bank degradation	Bank degradation	M
Habitat degradation	Alteration of riparian vegetation	M
	Alteration of in-channels habitat	M
Others		

Problems and constraints for river restoration

In alpine regions, the continuity of small headwaters is often interrupted by blocking debris. As a consequence, sediment and wood are stored, causing a decrease of sediment and wood in downstream river sections and catchment-wide impacts on the ecosystems.

Large impoundments of storage power plants in the alpine region result in a reduction of the natural flow and a disruption of the sediment regime at a local scale. These impoundments also affect the downstream sections particularly with regard to altered water temperature or flow regime and/or decreased water quantity, depending on the operating method of the storage power plant.

Water abstraction due to hydropower production leads to residual water flow in the river channel, which can result in a completely dry riverbed at its maximum extent. Furthermore, water abstraction from rivers through inter-basin flow transfer schemes causes reduced flow of the donor river system.

Flush flow of water storage basins aiming to get rid of accumulated fine sediments, creates artificial flood events and affects the whole river system downstream of the dam.

Measures

Common restoration practice

Most of the measures taken in glacial rivers aim to restore the flow alteration. Most important is the restoration of the natural flow regime, the re-establishment of the natural flow dynamics and the increase of water flow quantity in case of residual water flow. Furthermore, natural sediment regime and wood delivery must be restored.

Score per measure category/measure of relevance, effect in-channel, effect on the floodplain and costs the measure in comparison to other measures within this river type (No = no relevance or effect, L = low relevance or effect, M = moderate relevance or effect, H = high relevance or effect of the measure) and indication a prioritisation of measures (L = low priority, M = moderate priority, H = high priority).

Measure category	Measure	Relevance	Effect in-channel	Effect floodplain	Costs	Prioritisation
Decrease pollution	Decrease point source pollution	L	L	No	H	L
	Decrease diffuse pollution input	L	L	No	H	L
Water flow quantity	Reduce surface water abstraction	H	H	No	M	H
	Improve water retention	L	L	No	L	L
	Reduce groundwater abstraction	No				
	Improve water storage	L	L	No	H	L
	Increase minimum flow	H	H	No	M	H
	Water diversion and transfer	H	H	No	M	H
	Recycle used water	No				
	Reduce water consumption	No				
Sediment quantity	Add/feed sediment	H	H	No	M	H
	Reduce undesired sediment input	L	L	No	H	L
	Prevent sediment accumulation	No				
	Improve continuity of sediment transport	H	H	No	M	H
	Trap sediments	No				
	Reduce impact of dredging	No				
Flow dynamics	Establish natural environmental flows	H	H	No	M	H
	Modify hydropeaking	L	L	No	M	H
	Increase flood frequency and duration	L	L	No	M	H
	Reduce anthropogenic flow peaks	L	L	No	M	H
	Shorten the length of impounded reaches	H	H	No	M	H
	Favour morphogenic flows	H	H	No	M	H
Longitudinal connectivity	Install fish pass, bypass, side channels	L	L	No	H	M
	Install facilities for downriver migration	L	L	No	H	L
	Manage sluice, weir, and turbine operation	H	H	No	M	H
	Remove barrier	H	H	No	H	H
	Modify or remove culverts, syphons, piped rivers	No				
In-channel habitat condi-	Remove bed fixation	L	L	No	L	L

Measure category	Measure	Relevance	Effect in-channel	Effect floodplain	Costs	Prioritisation
tions	Remove bank fixation	L	L	No	L	L
	Remove sediment	L	L	No	L	L
	Add sediment (e.g. gravel)	L	L	No	L	L
	Manage aquatic vegetation	L	L	No	L	L
	Remove in-channel hydraulic structures	L	L	No	L	L
	Creating shallows near the bank	L	L	No	L	L
	Recruitment or placement of large wood	L	L	No	L	L
	Boulder placement	No				
	Initiate natural channel dynamics	L	L	No	L	L
	Create artificial gravel bar or riffle	L	L	No	L	L
Riparian zone	Develop buffer strips to reduce nutrients	L	L	No	M	L
	Develop buffer strips to reduce fine sediments	No				
	Develop natural vegetation on buffer strips	No				
River planform	Re-meander water course	No				
	Widening or re-braiding of water course	No				
	Create a shallow water course	No				
	Narrow over-widened water course	No				
	Create low-flow channels	No				
	Allow/initiate lateral channel migration	No				
	Create secondary floodplain	No				
Floodplain	Reconnect backwaters, oxbow-lakes, wet-lands	No				
	Create backwaters, oxbow-lakes, wetlands	No				
	Lower embankments, levees or dikes	No				
	Replace embankments, levees or dikes	No				
	Remove embankments, levees or dikes	No				
	Remove vegetation	No				

Problems and constraints with common restoration practice

Hydrology must be considered as the most important process because it affects the whole river system.

Impoundment and water abstraction are relevant topics because of the dynamism of the hydropower sector and the need to mitigate and remediate adverse ecological impacts.

Hydrological measures focused on mitigating the flow alteration are often applied at a local/small scale without solving the hydrological dynamics that result from catchment-wide activities. Individual measures at each hydropower plant are usually set without considering the downstream or upstream situation.

Considering the restoration of the sediment regime, the catchment scale approach is essential. Even though the sediment regime in highland river types is usually not compromised, the building of check dams and the subsequent retention of sediment and wood can cause negative effects. These effects (e.g. increased bed and bank erosion, bed incision, and negative sediment budget in wide floodplains) are visible far downstream at the lowland rivers. The input of sediment at downstream reaches is a common but unsustainable countermeasure. Restoring natural processes (e.g. restoration of water and sediment regime by removing blocking debris in the upper catchment) has a better effect on recovery, compared to local scale interventions (e.g. wood or gravel addition at a lower part of the river catchment).

Table 3. Promising measures and respective scale. The higher the scale the more effective the measure.

	Ecological key factor				
Scale	Temperature and light regime (System conditions)	Flow regime (Hydrology)	Profile variation, substrate heterogeneity and organic material (Morphology)	Oxygen regime, nutrient and toxic load (Chemistry)	Connectivity (Biology)
Catchment ↓	Ground water				
	Surface water hydrology				
	Sediment regime				
		Free flow	↔	Connectivity	
			Nutrients and organic load		
				Toxicants	
River stretch	Riparian zone				
		Profile			
		Maintenance			
Site		Habitat			

Promising and new measures

Individual mitigation measures at each hydropower plant should be coordinated at a catchment scale. A master-plan at larger scale is necessary.

Water sections affected by residual water flow are restored by re-establishing a nature-like flow regime. The base flow will be increased and morphological improvements of key habitats could additionally mitigate the pressure.

Dam or weir removal is a promising measure in the alpine region to re-activate the stored sediment and to ensure a continuous sediment flow. Especially, at the scale of the catchment such measures will sort strong effects. The river is not considered in solitude but is seen and dealt with as part of its catchment.

Especially in glacial rivers, catchment-wide measures and measures restoring the natural system conditions (processes that fit to the current climatological and geo-morphological conditions) are most effective (see table below).

Monitoring scheme

Monitoring schemes should follow some basic principles that apply to all river types:

- Biotic as well as abiotic variables should be monitored. The restoration measures might have succeeded to create the desired habitats but the effect on biota might be limited due to other pressures at larger scales which have not been addressed in the restoration project.
- In-channel, riparian, as well as floodplain conditions should be monitored. Besides the biological quality elements relevant for the Water Framework Directive, restoration can also have positive effects on other semi-aquatic and terrestrial organism groups, like ground beetles and floodplain vegetation. Indeed, there is empirical evidence that effects on other organism groups can be larger.
- Monitoring has to be conducted at appropriate spatial and temporal scales that reflect (i) the habitat needs of the organisms (e.g. monitoring microhabitat substrate patches for macroinvertebrates, mesohabitat features for fish), (ii) all life stages (e.g. monitoring in-channel and riparian habitats for macroinvertebrates with terrestrial life-stages), (iii) and the reproductive cycle as well as dispersal abilities (long-term monitoring to also cover effects of restoration on long-lived species and weak dispersers).
- Looking at the spatial and time scale of many current restoration measures macro-invertebrates are most suited for river monitoring. Fish population are strongly managed and reflect larger scale conditions, macrophytes bear a long history as they disappear only slowly and algae reflect to short time scales and very, very local conditions. Floodplains are large scaled and best be monitored by vegetation. Riparian zone can be monitored by using vegetation or carabid beetles.
- A Before-After-Control-Impact design should be applied to allow disentangling the effect of restoration from general trends in the whole river or catchment.
- However, the final selection of the organism groups, and spatial / temporal scales monitored strongly depends on the objectives and applied measures. Of course, it is reasonable to focus on the abiotic and biotic variables and scales that potentially have been affected by the restoration measures (e.g. in-channel habitat conditions by in-channel measures).
- Monitoring results should be used for adaptive management, i.e. to react on unanticipated effects and trends, and this should be included in the planning from the beginning ("Plan-B").

For further reading and practical guidelines we refer to the handbook of the River Restoration Centre (River Restoration Centre 2011).

The relevance of a variable at the scale of the river, riparian zone and floodplain scored in comparison to other variables within this river type (No = no relevance, L = low relevance, M = moderate relevance, H = high relevance)

Variable group	Variable	River	Riparian zone	Floodplain
River hydrology	Water quantity, Flow regime type, Average monthly flows	H	L	No
In-channel hydraulics	Baseflow index, Morphologically meaningful discharges	H	M	No
Floodplain morphology		No	No	No
In-channel morphology	Profile (longitudinal, transversal), sediment regime and budget,	H	M	No
	Meso-/micro-structures	H	L	No
Chemistry	Nutrients	L	L	No
	Toxicants	L	L	No
	Others			
	Water temperature	H	No	No
Biology	Algae	L	No	No
	Macrophytes	L	L	No
	Macroinvertebrates	H	H	No
	Fish	H	H	No
	Floodplain/riparian vegetation	L	L	No
	Terrestrial fauna	No	L	No

Fact sheet: Very large rivers

General description

Valley- and planform	Various planforms possible depending on slope. In general due to gentle slopes sinuous or meandering, but often also island-braided or sometimes anastomosing. Valley form unconfined with wide floodplains
Hydrology	More or less predictable seasonal discharge patterns with a mixture of snow-, rain- or groundwater-fed.
Morphology	Wide channels with high width/depth ration, gentle inner bends and steeps outer bends, bare and vegetated islands. Besides the main channels there are side channels and downstream connected oxbows.
Chemistry	The water quality is mostly eutrophic, sometimes mesotrophic. Large rivers are calcareous/mixed or sometimes organic rivers.
Riparian zone	Generally vegetated with soft-wooded floodplain forest (Populus, Salix), herbaceous grasslands or bare (sand, gravel). Extensive floodplains (several hundred to kms wide) with disconnected water bodies (oxbows, scour holes) in various successional stages. These water bodies can remain for decades or centuries. Soil type, inundation frequency and duration direct the terrestrial and aquatic vegetation community.

Figure: The River Don (Russia) still has significant near-natural stretches along its course.

Large rivers have upstream catchments > 10,000 km^2 and the very large even > 100,000 km^2 (e.g. Danube, Rhine, Elbe, Vistula and several Russian rivers). Due to their size the flow regime is more stable and the role of vegetation is less than in small and medium-sized rivers. Most very large rivers are situated in the lowland i.e. below 200 m ASL though large rivers are also found in the midland regions (e.g. the confluence of the River Inn (25,700 km^2) with the Danube is at 291 m ASL).

Reaches of large rivers are diverse and could be of the following REFORM types (15 – 22) having gravel, sand, silt and clay as the dominant sediment and being braided, meandering, sinuous, straight or anabranching depending on slope and sediment supply. Depending on width and depth (vegetated) islands occur.

Most large rivers originally had and some still have wide floodplains covered with soft-wooded or hard-wooded forest or agricultural land use ranging from extensive grasslands mowed for hay or intensive crop production such as maize. In the floodplains there are water bodies either in permanent connection with the main channel or only connected during flood events. These predominantly stagnant water bodies are more comparable to lakes than to rivers.

The present key reference for large rivers in Europe is Tockner et al. (2008). We recommend to consult this standard book as a first gateway for further information on specific large rivers.

Pressures

Major pressures

Large rivers are generally impacted by multiple pressures due to pollution originating from point and diffuse sources, hydromorphological modifications to serve water supply for agricultural, industries and drinking water, navigation, energy production, flood protection and fragmented by dams. The most regulated are found in central and southern Europe and the less modified in Eastern and Northern Europe. More details on six large river case studies and the impacts of pressures are documented in a specific REFORM deliverables on large rivers (Van Geest et al. 2015)

Scores of pressure level imposed on very large rivers categorised according to pressure category and pressure, respectively (score in comparison to other pressures within this river type: No = no pressure/stress, L = low pressure/stress, M = moderate pressure/stress, H = high pressure/stress).

Pressure category	**Pressure**	**Score**[1]
Point sources	Point sources	M
Diffuse sources	Diffuse sources	H
Water abstraction	Surface water abstraction	L / M
	Groundwater abstraction	N / L
Flow alteration	Discharge diversions and returns	N / L
	Interbasin flow transfer	L
	Hydrological regime modification including erosion due to increase in peak discharges	L
	Hydropeaking	L
	Flush flow	N
	Impoundment	H
Barriers/Connectivity	Artificial barriers upriver from the site	M
	Artificial barriers downriver from the site	H
Channelization	Channelisation / cross section alteration (e.g. deepening) including erosion due to this	H
	Sedimentation	L
	Channel fixation preventing lateral migration	H
Bank degradation	Bank degradation	H
Habitat degradation	Alteration of riparian vegetation	H
	Alteration of in-channels habitat	H
Others	Floodplain embankment	M
	Invasive species	M

[1] Score differs substantially between individual large rivers e.g. abstraction and diversion occur in large Mediterranean rivers and less elsewhere. Point sources have been a significant problem in many large rivers, but are treated by WWTP. Impoundment in particular for water supply, energy production and navigation.

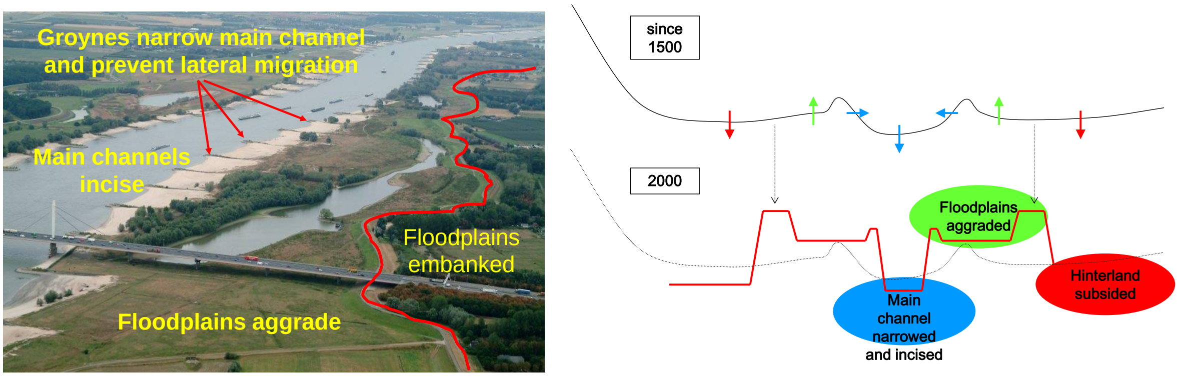

Figure: Aerial view of the Waal branch of the River Rhine (the Netherlands) showing several hydromorphological modifications and their impacts and a schematic presentation of the morphological changes.

Problems and constraints for river restoration

Large rivers cannot be restored to original state and thus can at best be partially rehabilitated. Furthermore the options for rehabilitation are directed by boundary conditions (altered discharge regimes of water and sediments) which causes may be distant or in other member status. Rehabilitation of the very large rivers requires international cooperation and negotiation. Because most large rivers serve multiple socio-economic functions the major challenge is the trade-off between rehabilitation and these functions and to identify synergies e.g. removing bank protection to create near-natural riparian zones may conflict with navigation due to enlarge sedimentation in the main channel thereby reducing navigational depth and uncontrolled growth of floodplain forest and herbaceous vegetation may enlarge flood risks. Large rivers in particular are colonised rapidly by invasive species, because many are interconnected through canals facilitating the distribution of benthic invertebrates and fish. Simply due to the size and scale restoration and mitigation measures for large rivers are expensive e.g. the estimated cost for a vertical slot fish passage in the Iron Gate dam to improve sturgeon migration in the Danube is 20 M€.

Measures

Common restoration practice

Restoration practice in large rivers started by improving the water quality in particular by treating industrial and municipal waste water (point sources) and more recently focusses on improving migration through fish passes at dam and weirs, environmental flow regimes for large hydropower schemes and improving the ecological quality of riparian zones and floodplains either by removing bank protection, re-connecting side channels and changing land use from agriculture and forestry to nature. More and more synergy is sought between flood protection and ecological improvement. In-channel measures, e.g. gravel supply downstream dams, are relatively rare in large rivers and reduction of pollution originating from diffuse sources almost fully depends on measures in the catchment of the tributaries.

Score per measure category/measure of relevance, effect in-channel, effect on the floodplain and costs the measure in comparison to other measures within this river type (No = no relevance or effect, L = low relevance or effect, M = moderate relevance or *effect, H = high relevance or effect of the measure) and indication a prioritisation of measures (L = low priority, M = moderate priority, H = high priority). Note: when relevance is no or low then not further specified. Information on costs is not specified, because they are too site specific or unknown.*

Measure category	Measure	Relevance	Effect in-channel	Effect floodplain	Prioritisation	Where or why?
Decrease pollution	Decrease point source pollution	H	H	M	H	
	Decrease diffuse pollution input	M	L	L	M	Tributary catchment
Water flow quantity	Reduce surface water abstraction	L				
	Improve water retention	M	L	H	M	Floodplain
	Reduce groundwater abstraction	L				
	Improve water storage	M	L	H	M	Floodplain
	Increase minimum flow	H	H	M	H	Hydropower
	Water diversion and transfer	M	M	M	M	Mediterranean
	Recycle used water	N				
	Reduce water consumption	L				
Sediment quantity	Add/feed sediment	M	H	L	M	Below dams
	Reduce undesired sediment input	L				
	Prevent sediment accumulation					
	Improve continuity of sediment transport	H	H	L	M	Impounded stretches
	Trap sediments	L				
	Reduce impact of dredging	M	H	L	?	Navigation
Flow dynamics	Establish natural environmental flows	M	M	M	M	Hydropower
	Modify hydropeaking	H	H	L	H	Hydropower
	Increase flood frequency and duration	H	L	H	H	Incised channels and aggradated floodplains; non-active floodplains ('polders')
	Reduce anthropogenic flow peaks					
	Shorten the length of impounded reaches	N				
	Favour morphogenic flows	L				
Longitudinal connectivity	Install fish pass, bypass, side channels	H	M	L	H	Dams and weirs
	Install facilities for downriver migration	M	L	L	M	Only where required e.g. eel
	Manage sluice, weir, and turbine operation	M	L	L	L	
	Remove barrier	L				
	Modify or remove culverts, syphons, piped rivers	N				

Measure category	Measure	Relevance	Effect in-channel	Effect floodplain	Prioritisation	Where or why?
In-channel habitat conditions	Remove bed fixation	L				
	Remove bank fixation	H	H	L	H	Natural banks allowing for sedimentation and erosion
	Remove sediment	L				
	Add sediment (e.g. gravel)	M	H	L	M	Below dams
	Manage aquatic vegetation	N				
	Remove in-channel hydraulic structures	L				
	Creating shallows near the bank	H	H	L	H	Plankton production; Spawning and nursery habitat for fish
	Recruitment or placement of large wood	H	H	L	H	Habitat diversity. Substrate for benthic invertebrates; Shelter for fish.
	Boulder placement	N				
	Initiate natural channel dynamics	M	H	L	M	Side channels
	Create artificial gravel bar or riffle	N				
Riparian zone	Develop buffer strips to reduce nutrients	L				
	Develop buffer strips to reduce fine sediments	N				
	Develop natural vegetation on buffer strips	H	L	H	H	
River planform	Re-meander water course	L				
	Widening or re-braiding of water course	H	H	M	M	In large rivers without navigation
	Create a shallow water course	H	H	L	H	Spawning and nursery habitat for fish
	Narrow over-widened water course	N				
	Create low-flow channels	H	H	L	H	Spawning and nursery habitat for fish
	Allow/initiate lateral channel migration	H	H	H	L	Conflict with other functions. Probably complex to achieve
	Create secondary floodplain	N				
Floodplain	Reconnect backwaters, oxbow-lakes, wetlands	H	H	H	H	Enlarge habitat diversity in particular for young fish
	Create backwaters, oxbow-lakes, wetlands	M	L	H	M	
	Lower embankments, levees or dikes	M	L	M	M	To increase inundation frequency and duration
	Replace embankments, levees or dikes	L				Flood protection measure to enlarge storage and discharge capacity
	Remove embankments, levees or dikes	M	L	M	M	To increase inundation frequency and duration
	Remove vegetation	L				Flood protection - terrestrial to enlarge discharge capacity

Figure: Restoration measures to improve longitudinal connectivity: the fish pass near Hagestein in the Neder-Rijn. Monitoring showed that among 38 fish species numerous diadromous lampreys migrated through this fish pass)

Figure: Restoration measure to improve floodplains: Floodplain lakes which inundate a limited number of days per year harbour limnophilic fish species such as tench

Development of isolated water bodies and marshes

During past decades, a number of lakes and ponds have been excavated in the floodplains along the Delta Rhine. Such created or rehabilitated lakes were readily colonized by various submerged macrophytes in the years after excavation. In the first four years, pioneer species such as Chara vulgaris, Potamogeton pusillus, and Elodea nuttallii dominated these lakes. Remarkably, after this first stage of macrophyte dominance, a large proportion of the excavated lakes lost their aquatic vegetation within a few years. Only lakes that were small (< 1-2 ha) and shallow (< 1.5-2 m) remained vegetated by submerged macrophytes (Van Geest, 2005).

Floodplain lake morphometry, as well as amplitude of water-level fluctuations during non-flooded conditions, strongly determined cover and composition of aquatic vegetation. During non-flooded conditions along the Rhine, lake water-level fluctuations are largely driven by groundwater connection to the river. Hence, water-level fluctuations are largest in lakes close to the main channel in strongly fluctuating sectors of the river and smallest in more remote lakes. Additionally, water-level fluctuations are usually small in old lakes, mainly due to reduced groundwater hydraulic conductivity resulting from accumulated cohesive clay and silt on the bottom. The reduced amplitude of water-level fluctuations with lake age has a strong impact on macrophyte succession in floodplain lakes from desiccation-tolerant species (e.g. Chara spp.) in young lakes to desiccation-sensitive species (e.g. Nuphar lutea, Figure 5.11) in old lakes (Van Geest, 2005).

Floodplain lakes with abundant vegetation, which inundate less than 20 days per year have low fish species richness, but provide suitable habitat for the reproduction of limnophilic species such as Tench (Tinca tinca), Rudd (Rutilus erythrophtalmus) and Crucian carp (Carassius carassius) (Grift et al. 2006; Figure 5.11). The proportion of limnophilic species in these lakes is, however, outnumbered by eurytopic species such as Bream (Abramis brama). Some limnophylic species such as weatherfish (Misgurnus fossilis) and Ten-spined stickleback (Pungitius pungitius) were extremely rare, suggesting that most remote and seldom flooded lakes have disappeared completely from the floodplains along the Delta Rhine.

Problems and constraints with common restoration practice

Large rivers fulfil major and often vital socio-economics functions. Rehabilitation programmes needs to be balanced with flood protection, energy production, navigation and freshwater supply for agriculture and drinking water. This puts restrictions to the array of measures. Next, interventions to regulate rivers do have long-lasting impact (several decades or even over a century) on the hydromorphological processes and as such direct and restrict the range of possible measures. Furthermore measures are mostly morphological interventions in the riparian zone and floodplains i.e. at the reach scale. There are hardly to none (sub-)basin wide hydrological measures, because they require a trade-off with hydropower generation or freshwater supply for agriculture and win-win options are not so obvious as for flood protection. Lastly, simply due to the size and scale rehabilitating large rivers is expensive and time-consuming due to the wide range of stakeholders who need to understand and appreciate the benefits.

Promising and new measures

New possibilities arise in particular when programmes deliver multiple benefits. Room for the Rivers with the main aim to reduce flood risk gave unforeseen to reactivate embanked floodplains transforming agricultural land into a wetland (‘polder Noordwaard’, the Netherlands; several reopened polders previously used for agriculture or aquaculture e.g. Babina, Popina and Holbina polders, Danube delta, Romania). Training walls in the main channel replacing groynes or riprap can substantially naturalise riparian zones and creates shelter for benthic invertebrates and young fish against the impact of passing ships (River Rhine, the Netherlands, Figure:). The measure is meant to benefit flood protection, navigation during low discharges and improve the ecological quality of riparian habitats Adding sediments through gravel introduction below dams may rejuvenate instream habitats and banks and reduce channel incision and lowering of groundwater tables (Rhine downstream Kembs, border Germany and France). Enlarging flow discharges in impounded reaches where water is abstracted for hydropower rejuvenate habitats in the main channel and connected water bodies (River Rhône, France; Lamoroux et al. 2015).

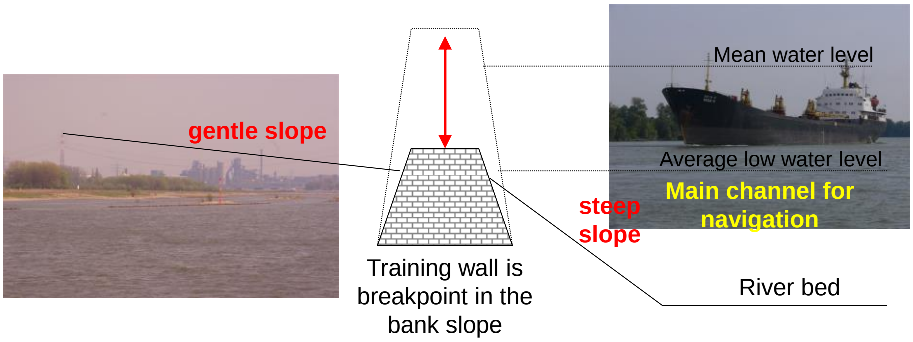

Figure: Training wall in the main channel creates a side channel with shelter.

Monitoring scheme

The present approach to monitor rehabilitation projects along large rivers too often suffers from a poor sampling design mostly caused by restricted financial budgets. Many evaluation programmes does follow a before-after or control-impact scheme. It regularly occurs the only the post-project situation is monitored without having documented the baseline. The consequence is that only conclusions can be drawn on what it now is, but not how it changed or improved. In addition, monitoring programme only last for a few years. Acknowledging the requirements of the WFD to demonstrate improvements and the large costs to realize large river rehabilitation programmes more emphasis should be given to proper monitoring schemes that allow drawing well-founded conclusions.

The relevance of a variable at the scale of the river, riparian zone and floodplain scored in comparison to other variables within this river type (No = no relevance, L = low relevance, M = moderate relevance, H = high relevance)

Variable group	**Variable**	**River**	**Riparian zone**	**Floodplain**
River hydrology		M	H	H
In-channel hydraulics		H	H	N
Floodplain morphology		N	L	H
In-channel morphology (including the shoreline)	Profile (longitudinal, transversal)	H	H	M (groundwater levels)
	Meso-/micro-structures	H	H	N
Chemistry	Nutrients	M	L	H
	Toxicants	H	M (heritage in sediments)	L (heritage in sediments)
Biology	Algae	L	L	M
	Macrophytes	M	M	H
	Macroinvertebrates	M	H	H
	Fish	H	H	M
	Floodplain/riparian vegetation	N	H	H
	Terrestrial fauna	N	H	M

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Appendix 1 More extensive explanation of Table on measures

Measure category	Measure	Measure
Decrease point source pollution	Decrease point source pollution	Decrease point source pollution
Decrease diffuse nutrient or pollution input (other than buffer strips!)	Decrease diffuse pollution input	Decrease diffuse nutrient or pollution input (other than buffer strips!)
Water flow quantity	Reduce surface water abstraction	Reduce water surface water abstraction without return
	Improve water retention	Improve water retention (e.g. on floodplain, urban areas)
	Reduce groundwater abstraction	Reduce groundwater abstraction
	Improve water storage	Improve/create water storage (e.g. polders)
	Increase minimum flow	Increase minimum flow (to generally increase discharge in a reach or to improve flow dynamics)
	Water diversion and transfer	Water diversion and transfer to improve water quantity
	Recycle used water	Recycle used water (off-site measure to reduce water consumption)
	Reduce water consumption	Reduce water consumption (other measures than recycling used water)
Sediment quantity	Add/feed sediment	Add/feed sediment (e.g. downriver from dam)
	Reduce undesired sediment input	Reduce undesired sediment input (e.g. from agricultural areas or from bank erosion other than riparian buffer strips!)
	Prevent sediment accumulation	Prevent sediment accumulation in reservoirs
	Improve continuity of sediment transport	Improve continuity of sediment transport (e.g. manage dams for sediment flow)
	Trap sediments	Trap sediments (e.g. building sediment traps to reduce washload)
	Reduce impact of dredging	Reduce impact of dredging
Flow dynamics	Establish natural environmental flows	Establish environmental flows / naturalise flow regimes (does focus on discharge variability)
	Modify hydropeaking	Modify hydropeaking
	Increase flood frequency and duration	Increase flood frequency and duration in riparian zones or floodplains
	Reduce anthropogenic flow peaks	Reduce anthropogenic flow peaks
	Shorten the length of	Shorten the length of impounded reaches

Measure category	Measure	Measure
	impounded reaches	
	Favour morphogenic flows	Favour morphogenic flows (could also be considered a measure to improve planform or in-channel habitat conditions
Longitudinal connectivity	Install fish pass, bypass, side channels	Install fish pass, bypass, side channel for upriver migration
	Install facilities for downriver migration	Install facilities for downriver migration (including fish friendly turbines)
	Manage sluice, weir, and turbine operation	Manage sluice, weir, and turbine operation for fish migration
	Remove barrier	Remove barrier (e.g. dam or weir)
	Modify or remove culverts, syphons, piped rivers	Modify or remove culverts, syphons, piped rivers
In-channel habitat conditions	Remove bed fixation	Remove bed fixation
	Remove bank fixation	Remove bank fixation
	Remove sediment	Remove sediment (e.g. mud from groin fields)
	Add sediment (e.g. gravel)	Add sediment (e.g. gravel)
	Manage aquatic vegetation	Manage aquatic vegetation (e.g. mowing)
	Remove in-channel hydraulic structures	Remove or modify in-channel hydraulic structures (e.g. groins, bridges)
	Creating shallows near the bank	Creating shallows near the bank
	Recruitment or placement of large wood	Recruitment or placement of large wood
	Boulder placement	Boulder placement
	Initiate natural channel dynamics	Initiate natural channel dynamics to promote natural regeneration
	Create artificial gravel bar or riffle	Create artificial gravel bar or riffle
Riparian zone	Develop buffer strips to reduce nutrients	Develop buffer strips to reduce nutrient input
	Develop buffer strips to reduce fine sediments	Develop buffer strips to reduce fine sediment input
	Develop natural vegetation on buffer strips	Develop natural vegetation on buffer strips (other reasons than nutrient or sediment input, e.g. shading, organic matter input)
River planform	Re-meander water course	Re-meander water course (actively changing planform)
	Widening or re-braiding of water course	Widening or re-braiding of water course (actively changing planform)

Measure category	**Measure**	**Measure**
	Create a shallow water course	Shallow water course (actively increasing level of channel-bed)
	Narrow over-widened water course	Narrow over-widened water course (actively changing width)
	Create low-flow channels	Create low-flow channels in over-sized channels
	Allow/initiate lateral channel migration	Allow/initiate lateral channel migration (e.g. by removing bank fixation and adding large wood)
	Create secondary floodplain	Create secondary floodplain on present low level of channel bed
Floodplain	Reconnect backwaters, oxbow-lakes, wetlands	Reconnect existing backwaters, oxbow-lakes, wetlands
	Create backwaters, oxbow-lakes, wetlands	Create semi-natural / artificial backwaters, oxbow-lakes, wetlands
	Lower embankments, levees or dikes	Lowering embankments, levees or dikes to enlarge inundation and flooding
	Replace embankments, levees or dikes	Back-removal of embankments, levees or dikes to enlarge the active floodplain area
	Remove embankments, levees or dikes	Remove embankments, levees or dikes or other engineering structures that impede lateral connectivity
	Remove vegetation	Remove vegetation

Appendix 2 Links to other European typologies

The AQEM river typology

The AQEM river typology covers 28 common European river types, which are representative for large parts of Europe (Table 1). Almost all of the river types have a catchment area <1000 km^2 ("small" and "medium-large" rivers).

Table 1. Overview of the AQEM river types. Column "ecoregion": number acc. to ILLIES (1978). Column "geology class": cal = calcareous, sil = siliceous, org = organic, alluv = alluvial deposits. Column "major degradation factors": M = degradation in stream morphology, O = Organic pollution, A = acidification, G = general degradation (not specified) (Hering et al. 2012).

	Stream type	Size class	Altitude class (m.a.s.l.)	Eco-region	Geology class	Major degradation factors
A01	Mid-sized streams in the Hungarian Plains	>100-1000 km2	200-800	11	sil (moraines)	O
A02	Mid-sized calcareous pre-alpine streams	>100-1000 km2	200-800	4	cal	M, O
A03	Small non-glaciated crystalline alpine streams	10-100 km2	>800	4	sil	M, O
A04	Mid-sized streams in the Bohemian Massif	>100-1000 km2	200-800	9	sil	M, O
C01	Mid-sized streams in the central sub-alpine mountains	>100-1000 km2	200-500	9	sil	O
C02	Small streams in the Carpathian	10-100 km2	200-500	10	flysch	O
C03	Mid-sized streams in the Carpathian	>100-1000 km2	200-500	10	flysch	O
D01	Small sand bottom streams in the German lowlands	10-100 km2	<200	14	sil	M, O
D02	Organic type brooks in the German lowlands	10-100 km2	<200	14	org	M, O
D03	Mid-sized sand bottom streams in the German lowlands	>100-1000 km2	<200	14	sil	M, O
D04	Small streams in lower mountainous areas of	10-100 km2	200-800	9	sil	M, O

	Stream type	Size class	Altitude class (m.a.s.l.)	Eco-region	Geology class	Major degradation factors
	Central Europe					
D05	Mid-sized streams in lower mountainous areas of Central Europe	>100-1000 km2	200-800	9	sil	M, O
H01	Mid-altitude mid-sized siliceous streams in North-Eastern Greece	>100-1000 km²	200-800	6	sil	O
H02	Mid-altitude large siliceous streams in Central and Northern Greece	>1000-10000 km2	200-800	6	sil	O
H03	Mid-altitude mid-sized calcareous streams in Western Greece	>100-1000 km2	200-800	6	cal	O
I01	Small-sized streams in the south-ern silicate Alps	10-100 km²	>800	4	sil	M
I02	Small-sized, calcareous streams in the Southern Apennines	10-100 km²	200-800	3	cal	G
I03	Mid-sized calcareous streams in the Northern Apennines	>100-1000 km2	200-800	3	cal	M
I04	Small lowland streams of the Po valley	10-100 km2	<200	3	sil	G
N01	Small Dutch lowland streams	≤10-100 km²	<200	13, 14	sil	G
N02	Small Dutch hill streams	≤10-100 km²	<200	14	sil	G
P01	Small-sized siliceous streams in lower mountainous areas of Southern Portugal	10-100 km2	200-800	1	sil	O
P02	Small-sized siliceous lowland streams of Southern Portugal	10-100 km2	<200	1	sil	O
P03	Medium-sized siliceous lowland streams of Southern Portugal	>100-1000 km2	<200	1	sil	O

	Stream type	Size class	Altitude class (m.a.s.l.)	Eco-region	Geology class	Major degradation factors
S01	Small lowland streams in Northern Sweden	10-100 km2	<200	22	sil	A
S02	Small mid-altitude streams in Northern Sweden	10-100 km2	200-800	22	sil	A
S03	Small mid-altitude streams in the Boreal Highlands	10-100 km2	200-800	20	sil	A
S04	Small high-altitude streams in the Boreal Highlands	10-100 km2	>800	20	sil	A
S05	Medium-sized lowland streams in the South Swedish lowlands	100-1000 km2	<200	14	sil	A, O

River typology of the WFD CIS Working Group

The Water Framework Directive (WFD) Common Implementation Strategy group (CIS) recently drafted a provisional river typology (Table 2). This typology is based on size, geology, altitude and catchment area (km^2). It follows system A of the WFD but is linked to all national typologies and as such usable in all European countries.

Table 2. Provisional river typology of the WFD CIS Working Group (March 2014).

	Broad type number and name	Altitude (masl)	Catchment area (km2)	Geology
1	Very large rivers (all Europe)	>10,000		
2	Medium-Large, siliceous/organic, lowland rivers	<200	100-10,000	Siliceous/Organic
3	Very small-small, siliceous/organic, lowland rivers	<200	<100	Siliceous/Organic
4	Medium-large, calcareous/mixed, lowland rivers	<200	100-10,000	Calcareous/Mixed
5	Very small-small, calcareous/mixed, lowland rivers	<200	<100	Calcareous/Mixed
6	Medium-large, siliceous, mid altitude rivers	200-800	100-10,000	Siliceous
7	Small, siliceous, mid altitude rivers	200-800	<100	Siliceous
8	Medium-large, calcareous/mixed, mid altitude rivers	200-800	100-10,000	Calcareous/Mixed
9	Very small-small, calcareous/mixed, mid altitude rivers	200-800	<100	Calcareous/Mixed
10	Siliceous, highland rivers	>800		Siliceous
11	Calcareous/mixed, highland rivers	>800		Calcareous/Mixed

	Broad type number and name	Altitude (masl)	Catchment area (km2)	Geology
12	Medium-large, Mediterranean, lowland rivers	<200	100-10,000	
13	Medium-large, Mediterranean, mid altitude rivers	200-800	100-10,000	
14	Very small-small, Mediterranean rivers		<100	

Table 3. Links between different river typologies with the river types that are used in the fact sheets.

		possible sub-classes geology	possible sub-classes geographical region	WFD CIS Working Group (March 2014)	European Topic Centre 2015	REFORM major classes	REFORM hymo classification	AQEM types
	High energy, highland rivers							
1	Small, sinuous-straight, highland rivers with bedrock-coarse mixed sediments	siliceous vs calcareous-mixed		CIS10, 11	ECT14, 15	REF1	1, 2, 3	A03, I01, S04
2	Mid-sized, sinuous-straight, highland rivers with bedrock-coarse mixed sediments	siliceous vs calcareous-mixed		CIS10, 11	ECT14, 15	REF1	1, 2, 3	A03, I01, S04
3	Small, cascade, step-pool/plain bed, riffle-pool, highland rivers with (very) coarse sediments	siliceous vs calcareous-mixed		CIS10, 11	ECT14, 15	REF2, REF3	4, 5, 6, 7	A03, I01, S04
4	Mid-sized, cascade, step-pool/plain bed, riffle-pool, highland rivers with (very) coarse sediments	siliceous vs calcareous-mixed		CIS10, 11	ECT14, 15	REF2, REF3	4, 5, 6, 7	A03, I01, S04
	Medium energy, mid altitude rivers with coarse to fine sediments							
5	Small, multi-thread, mid altitude rivers	siliceous vs calcareous-mixed	Mediterranean, Boreal	CIS6, 7, 12	ECT8, 9, 12, 19, 20	REF4	8, 9, 10, 11,15	C02, D04, S02, S03, A01, A04, C01, C03, D05, I04, P01, P02

		possible sub-classes geology	possible sub-classes geographical region	WFD CIS Working Group (March 2014)	European Topic Centre 2015	REFORM major classes	REFORM hymo classification	AQEM types
6	Mid-sized, multi-thread, mid altitude rivers	siliceous vs calcareous-mixed	Mediterranean, Boreal	CIS8, 9, 14	ECT10, 11, 13, 18	REF4	8, 9, 10, 11,15	A02, I03, I02, H01, H02, H03
7	Small, single-thread, mid altitude rivers	siliceous vs calcareous-mixed	Mediterranean, Boreal	CIS6, 7, 12	ECT8, 9, 12, 19, 20	REF5	12, 13, 14	C02, D04, S02, S03, A01, A04, C01, C03, D05, I04, P01, P02
8	Mid-sized, single-thread, mid altitude rivers	siliceous vs calcareous-mixed	Mediterranean, Boreal	CIS8, 9, 114	ECT10, 11, 13, 18	REF5	12, 13, 14	A02, I03, I02, H01, H02, H03
	Low energy, lowland rivers with fine to very fine bed sediment							
9	Small, single-thread, lowland rivers	siliceous vs calcareous-mixed	Mediterranean, Boreal	CIS2, 3, 12	ETC2, 3, 6, 19, 20	REF6	16, 17, 18, 20, 21	D01, D02, N01, N02, S01, D03, S05, I04, P01, P02
10	Mid-sized, single-thread, lowland rivers	siliceous vs calcareous-mixed	Mediterranean, Boreal	CIS4, 5, 13	ETC4, 5,7, 17	REF6	16, 17, 18, 20, 21	P03
11	Small, anabranching, lowland rivers	siliceous vs calcareous-mixed	Mediterranean, Boreal	CIS2, 3, 12	ETC2, 3, 6, 19, 20	REF7	19, 22	D01, D02, N01, N02, S01, D03, S05, I04, P01, P02

		possible sub-classes geology	possible sub-classes geographical region	WFD CIS Working Group (March 2014)	European Topic Centre 2015	REFORM major classes	REFORM hymo classification	AQEM types
12	Mid-sized, anabranching, lowland rivers	siliceous vs calcareous-mixed	Mediterranean, Boreal	CIS4, 5, 13	ETC4, 5,7, 17	REF7	19, 22	P03
	Others							
13	Very large rivers (all Europe)			CIS1	ETC1	REF6, REF7	16, 17, 18, 20, 21, 19, 22	
14	Glacial rivers (all Europe)			CIS10, CIS11	ETC16	REF1, REF2, REF3	1, 2, 3, 4, 5, 6, 7	

1. **Percentage of the number of pressure categories present per REFORM reach type.**

	Projects	Number of pressure categories								
REFORM reach types	(n)	0	1	2	3	4	5	6	7	8
0	6	0	33	33	33	0	0	0	0	0
5	21	0	24	38	10	19	10	0	0	0
8	17	0	6	29	35	24	0	6	0	0
11	13	0	8	46	15	8	15	0	0	8
13	3	0	0	67	0	0	0	33	0	0
14	132	3	10	45	26	15	0	0	1	0
15	4	0	0	25	75	0	0	0	0	0
17	6	0	33	50	0	17	0	0	0	0
18	66	3	11	47	26	11	3	0	0	0
19	2	0	0	0	50	50	0	0	0	0
21	100	4	3	54	26	8	3	2	0	0
23	22	0	9	50	32	9	0	0	0	0
10, 19, 22	1	0	0	0	0	100	0	0	0	0
14, 18, 21	74	4	9	36	24	19	5	0	1	0
20, 21, 22	2	0	50	50	0	0	0	0	0	0
21L	6	0	17	50	33	0	0	0	0	0
8, 15	4	0	0	25	50	0	25	0	0	0
Gravel-bed river reach	59	10	14	15	46	15	0	0	0	0
Mixed gravel-sand-bed river reach	9	0	11	44	44	0	0	0	0	0
no info	17	7	23	26	21	17	4	1	1	0
Organic-bed river reach	6	0	0	0	67	17	17	0	0	0
Sand-bed river reach	274	6	18	18	47	12	0	0	0	0
average		*2*	*13*	*34*	*30*	*15*	*4*	*2*	*0*	*0*
stdev		*3*	*13*	*19*	*21*	*22*	*7*	*7*	*0*	*2*