Environ Earth Sci (2015) 73:2079–2100
DOI 10.1007/s12665-014-3558-1

ORIGINAL ARTICLE

A review of assessment methods for river hydromorphology

B. Belletti · M. Rinaldi · A. D. Buijse ·
A. M. Gurnell · E. Mosselman

Received: 27 January 2014 / Accepted: 16 July 2014 / Published online: 2 August 2014

Abstract Numerous hydromorphological assessment methods have been developed in different countries during recent decades, with notable differences in their aims, scales, and approaches. Although these methods are increasingly applied to support river management, the strengths and limitations have been insufficiently investigated. This review of 121 methods analyses hydromorphological assessment methods dating from 1983 to 2013, identifying their main strengths, limitations, gaps, the potential to integrate different approaches, and the need for further improvements. For this purpose methods have been grouped into four categories: (1) physical habitat assessment; (2) riparian habitat assessment; (3) morphological assessment; (4) assessment of hydrological regime alteration. Seventeen categories of information covering general characteristics, recorded features and river processes encompassing over 90 features were recorded for each method reviewed, allowing a comparative analysis of the four assessment categories. The main gap in most methods is insufficient consideration of physical processes. Thus, an integrated hydromorphological analysis is recommended, where the morphological and hydrological components are the key parts to classify hydromorphological conditions. Additional physical and riparian habitat methods strengthen the link with ecological conditions.

Keywords Hydromorphology · Physical habitats · Riparian habitats · Hydrological regime · Morphological alteration

Introduction

In recent decades, hydromorphology has been developed as an umbrella discipline that links hydrology and geomorphology. It places the consideration of physical stream characteristics and processes at the centre of river management and restoration (Newson and Large 2006; Vaughan et al. 2009). Within Europe, it has developed rapidly and numerous methodologies have been proposed following the introduction of the EU Water Framework Directive (WFD; European Commission 2000). To assess and monitor all European water bodies, the WFD requires incorporating hydromorphology, in particular the hydrological regime (i.e. quantity and dynamics of water flow and connection to groundwater bodies), river morphology (i.e. channel dimensions and mobility, river bed structure and substrate calibre, and the structure of the riparian zone), and river continuity. Hydromorphological assessment can be defined to evaluate and classify both hydrological and geomorphological stream conditions. It includes those methods and procedures that identify and characterize hydromorphological features to assess river conditions. The many existing methods vary widely in terms of their concepts, aims, spatial scales, collected data and therefore their applicability.

Towards the end of the 20th century, hydromorphological assessment mainly focussed upon occurrence and

B. Belletti (✉) · M. Rinaldi
Department of Earth Sciences, University of Florence,
Via S. Marta 3, 50139 Florence, Italy
e-mail: barbara.belletti@unifi.it

A. D. Buijse · E. Mosselman
Deltares, Delft, The Netherlands

A. M. Gurnell
Queen Mary University of London, London, UK

E. Mosselman
Delft University of Technology, Delft, The Netherlands

spatial configuration of physical habitats (e.g., Platts et al. 1983; Plafkin et al. 1989; Raven et al. 1997, 2002). This because physical habitats were recognised as an important component in ecological studies aimed at explaining distributional patterns of organisms, and the composition and structure of biological communities (Fernández et al. 2011). During the last decade, it has been recognised that broader *river condition assessments* are needed that go beyond an inventory of physical habitats by including "pressure" or "response" variables with a stronger emphasis on river dynamics and processes (Fryirs et al. 2008). However, merging the full range of disciplinary approaches necessary to assess river conditions (hydrology, geomorphology, water quality, biology, ecology) in a cost-effective and integrated way, remains a challenge.

There have been a number of recent reviews of hydromorphological assessment methods that emphasise river habitat characterization (e.g., Weiss et al. 2008; Fernández et al. 2011), and there have also been attempts to standardise these habitat-based methods (CEN 2002; Parsons et al. 2004). However, many new promising methods employing a wider range of geomorphological concepts and approaches have been proposed in the last decade. Moreover the need and wish to apply assessment methods of hydromorphology has expanded rapidly following the adoption of the WFD. Indeed hydromorphological assessment is now carried out by many public agencies or subcontracted to consultancies, particularly within the European Union as a part of WFD implementation. Nevertheless often there is still insufficient awareness of the limitations and strengths of different methods, and how they should be integrated to ensure a comprehensive assessment.

In response to these needs, an extensive review analysis of existing hydromorphological methods (Rinaldi et al. 2013b) has been carried out in the context of restoring rivers for effective catchment management (REFORM; http://www.reformrivers.eu/), a collaborative EU project targeted to develop guidance and tools to make river restoration and mitigation measures more cost-effective. The review widened the scope compared to recent published reviews that mainly focussed on river habitat characterization (Raven et al. 2002; Mc Ginnity et al. 2005; Weiss et al. 2008; Fernández et al. 2011). It extended Fernández et al. (2011), who reviewed 55 mainly habitat-based assessment methods that have been developed worldwide, by incorporating a total of 121 methods. It identified the main strengths, limitations and gaps in existing methods, and proposed future directions for hydromorphological assessment. It also touched on methods specifically developed and applied in Europe, in relation to the implementation of the WFD. The review did not aim to discuss the scientific principles nor the concepts that underlie hydromorphological and river condition assessments, since these have already been reviewed recently (e.g. Fryirs et al. 2008), but it aimed to compare and discuss methods in a critic way, starting from the knowledge and expertise of the authors. The paper summarises the main outcomes of Rinaldi et al. (2013b).

Scope of the review

The range of application of the methods considered in this review varies from those applicable to small, wadeable streams to those suited to relatively large, non-wadeable rivers. It is restricted to physics-based assessments, i.e. methods that address all or some of the physical elements required for a hydromorphological evaluation. Therefore, methods for the assessment of longitudinal fish continuity are not included, as they have a biological focus, although they were included in the broader review of Rinaldi et al. (2013b). It also excludes physical habitat simulation models and environmental flows methods, as they differ in structure and approach from the truly hydromorphological (i.e. hydrological *and* geomorphological) assessments considered here. Indeed, habitat simulation and environmental flow methods aim to identify habitats and flow requirements, respectively, needed to achieve or maintain a specified river condition (Arthington 1998; King et al. 2008), rather than to directly assess hydromorphological condition, alteration and pressures. For some examples of habitat modelling approaches see Rinaldi et al. (2013b), and for environmental flows refer to Arthington (1998), King et al. (2008) and to the recent review of Poff and Zimmerman (2010).

The 121 methods reviewed, are listed in Table 1.

Categories of methods

An initial inspection of these hydromorphological methods revealed four broad categories of assessment, although a sharp delineation is difficult and some overlap between types inevitably exists. These were identified based on the main focus and objectives of each method, which were reflected in the spatial scale of application (Fig. 1): physical habitat assessment (PH), riparian habitat assessment (RH), morphological assessment (M) and assessment of hydrological regime alteration (HRA).

A temporal trend is apparent in the development and application of different approaches (Fig. 2). The earliest assessment methods started to appear at the beginning of the 1980s. Until the end of the 1990s, proposed methods can mainly be described as physical habitat survey procedures. This first phase reflects the progressive development of river restoration techniques, which initially consisted of

Table 1 Summary of hydromorphological assessment methods included in this review with percentage coverage regarding method characteristics (Ch), recorded features (Fe) and river processes (Rp) (for details see Table 2)

	Category	Year	Country	Acronym	Key reference	Ch	Fe	Rp
1	PH	1983	US	MESC	Platts et al. (1983)	47	56	33
2	PH	1987	Austria	Werth	Werth (1987)	59	48	17
3	PH	1989	Austria	WatercSt	Spiegler et al. (1989)	53	59	17
4	PH	1989	US	QHEI	Rankin (1989)	59	63	33
5	PH	1992	Sweden	RCE	Petersen (1992)	47	33	33
6	PH	1993	Australia	SRS	Anderson (1993)	59	41	33
7	PH	1993	Belgium	SEvalW	Schneiders et al. (1993)	47	33	17
8	PH	1994	Belgium	SK	Wils et al. (1994)	35	11	0
9	PH	1996	Austria	GEBD (RSR)	Buhmann and Hutter (1996)	59	56	17
10	PH	1996	France	Qualphy	Denortier and Goetghebeur (1996)	59	63	33
11	PH	1996	US	RSAT	Galli (1996)	41	41	17
12	PH	1997	England	RHS	Raven et al. (1997)	53	67	50
13	PH	1997	Poland	EcomorphEval	Ilnicki and Lewandowski (1997)	47	41	33
14	PH	1997	US	FFHSIP	Overton et al. (1997)	41	33	17
15	PH	1997	US	VSMM	US Environmental Protection Agency (1997)	59	52	33
16	PH	1998	Austria	AssRivSt	Muhar and Jungwirth (1998)	59	67	50
17	PH	1998	Austria	RATyrol	BUWAL (1998)	41	26	17
18	PH	1998	Denmark	DSFI	Danish Env. Protection Agency (1998)	35	7	0
19	PH	1998	France	SEQ-P	Agences de ĹEau (1998)	59	63	33
20	PH	1998	Switzerland	ModConc	Liechti et al. (1998)	41	37	33
21	PH	1998	US	MCSH (NAWQA)	Fitzpatrick et al. (1998)	47	37	0
22	PH	1998	US	RHVSA-EMAP	Lazorchak et al. (1998)	41	37	0
23	PH	1999	Australia	ISC	Ladson et al. (1999)	65	30	33
24	PH	1999	Denmark	Aarhus	Kaarup (1999)	47	18	17
25	PH	1999	Denmark	NPHI	National Environmental Research Institute (1999)	47	37	0
26	PH	1999	Denmark	PhysSC	Skriver et al. (1999)	41	41	0
27	PH	1999	US	PHC (EMAP)	Kaufmann et al. (1999)	41	41	0
28	PH	1999	US	RBP	Plafkin et al. (1989), Barbour et al. (1999)	59	56	33
29	PH	2000	Australia	HPM	Davies et al. (2000)	59	48	17
30	PH	2000	England	MesoH	Tickner et al. (2000)	41	11	0
31	PH	2000	Germany	LAWA-FS-MToL	LAWA (2000)	59	48	50
32	PH	2000	US	WCE	Oregon Watersh. Enhanc. Board (2000)	71	52	33
33	PH	2001	Austria	NÖMORPH	Freiland Umeltconsulting (2001a, b)	59	41	17
34	PH	2001	Germany	BfG–WW	Bundesanstalt für Gewässerkunde (2001)	47	56	50
35	PH	2001	US	SCA	Yetman (2001)	47	48	50
36	PH	2001	US	SRHRAP	Starr and McCandless (2001)	41	41	33
37	PH	2002	Germany	LAWA-FS-SToL	LAWA (2002a)	59	52	50
38	PH	2002	Germany	LAWA-OS	LAWA (2002a, b)	53	37	50
39	PH	2002	Italy	IFF	Siligardi et al. (2002)	59	37	17
40	PH	2002	Spain	IHF	Pardo et al. (2002)	41	18	0
41	PH	2002	Sweden	BiotopeMap	Halldén et al. (2002)	65	44	17
42	PH	2002	US	HHEI	Ohio Env. Protection Agency (2002)	59	30	0
43	PH	2002	US	MinHWCP	Minnesota Pollution Control Ag. (2002)	41	44	17
44	PH	2003	Denmark	DHQI	Pedersen and Baattrup-Pedersen (2003)	71	41	17
45	PH	2003	England	GeoRHS	Environment Agency (2003)	59	48	67
46	PH	2003	US	MNHWA	Crowe and Kudray (2003)	47	26	33
47	PH	2004	Australia	AusRivAs-PAP	Parsons et al. (2004)	65	70	50
48	PH	2004	England	URS	Davenport et al. (2004)	53	56	50

Table 1 continued

	Category	Year	Country	Acronym	Key reference	Ch	Fe	Rp
49	PH	2004	Germany	GSI	Feld (2004)	59	52	17
50	PH	2004	US	BURP	Idaho Dep. Env. Quality (2004)	53	37	17
51	PH	2004	US	SEvalAH	Kansas Dep. of Widelife and Parks (2004)	53	37	33
52	PH	2004	US	VSGA	Vermont Agency of Natural Resources (2010)	53	63	67
53	PH	2004	US	WSAss	US Environmental Protection Agency (2004)	47	44	33
54	PH	2005	Italy	CARAVAGGIO	Buffagni et al. (2005)	59	70	50
55	PH	2005	Portugal	HCI	Oliveira and Cortes (2005)	53	26	0
56	PH	2005	US	NWHI	Wilhelm et al. (2005)	41	22	17
57	PH	2006	Czech Rep.	EcoRivHab	Matoušková (2006)	65	52	33
58	PH	2006	Spain	HIDRI	Munné et al. (2006)	71	59	17
59	PH	2006	US	SIH	US Forest Service (2006)	53	44	50
60	PH	2007	Netherlands	Handboek HYMO	Dam et al. (2007)	53	41	67
61	PH	2007	Slovakia	HAP–SR	Lehotský and Grešková (2007)	59	63	67
62	PH	2008	South Africa	IHI	Kleynhans et al. (2008)	53	41	33
63	PH	2009	NZ	SHAP	Harding et al. (2009)	53	59	17
64	PH	2009	Poland	MHR	Ilnicki et al. (2009)	59	56	33
65	PH	2009	Slovenia	SI_HM	Tavzes and Urbanic (2009)	53	67	50
66	PH	2009	US	SCS-SH	Maine Dep. of Env. Protection (2009)	59	48	50
67	PH	2009	US	SVAP	US Department of Agriculture (2009)	53	59	67
68	PH	2010	Austria	HYMO	Mühlmann (2010)	47	41	50
69	PH	2010	China	USM	Xia et al. (2010)	41	44	50
70	PH	2010	France	CarHyCE	ONEMA (2010)	35	44	33
71	PH	2010	US	MBSS	Stranko et al. (2010)	47	52	17
72	PH	2011	Ukraine	UA-FS	Scheifhacken et al. (2012)	47	48	17
73	PH	2012	Ireland	RHAT	Murphy and Toland (2012)	65	67	67
74	RH	1995	US	HGM	Smith et al. (1995)	35	7	17
75	RH	1998	Italy	BSI & WSI	Braioni and Penna (1998)	59	67	0
76	RH	1998	Quebec	IQBR	Saint-Jaques and Richard (1998)	35	22	0
77	RH	1998	Spain	QBR	Munné and Prat (1998), Munné et al. (2003)	47	33	17
78	RH	1998	US	PFC	Prichard et al. (1998)	29	41	50
79	RH	2000	US	RWA	Oregon Watersh. Enhanc. Board (2000)	47	22	17
80	RH	2000	US	VRRA	Winward (2000)	41	15	17
81	RH	2003	US	VARH	Ward et al. (2003)	35	41	33
82	RH	2005	Australia	RARC	Jansen et al. (2005)	35	22	0
83	RH	2005	Australia	TRARC	Dixon et al. (2005)	35	22	0
84	RH	2006	Spain	IVF	Munné et al. (2006)	47	41	0
85	RH	2007	South Africa	VEGRAI	Kleynhans et al. (2007)	47	30	0
86	RH	2010	Spain	RFV	Magdaleno et al. (2010)	47	22	0
87	RH	2011	Spain	RQI	González and García (2011)	47	63	50
88	RH	2012	Australia	RVC_RCI	Healey et al. (2012)	47	22	17
89	M	1984–1986	US	CEMs	Schumm et al. (1984), Simon and Hupp (1986)	29	29	67
90	M	1994	US	SCRS	Harrelson et al. (1994)	41	48	33
91	M	1995	US	RGAs	Ministry of Env. (1999), Simon and Downs (1995)	59	41	33
92	M	1996	US	NCD	Rosgen (1996)	53	52	33
93	M	1998	England	FA	Environment Agency (1998)	65	81	83
94	M	1998	England	SRH	Thorne (1998)	53	70	50
95	M	2000	South Africa	GI	Rowntree and Wadeson (2000)	71	56	33
96	M	2000	US	CMA	Oregon Watershed Enhancement Board (2000)	65	26	33

Table 1 continued

	Category	Year	Country	Acronym	Key reference	Ch	Fe	Rp
97	M	2005	Australia	RSF	Brierley and Fryirs (2005)	65	56	67
98	M	2005	South Africa	GAI	Kleynhans et al. (2005)	53	44	83
99	M	2006	Spain	HIDRI-P1	Munné et al. (2006)	41	11	0
100	M	2006	US	WARSSS	Rosgen (2006)	53	56	67
101	M	2007	Czech Republic	HEM	Langhammer (2007)	71	48	50
102	M	2007	Spain	IHG	Ollero et al. (2007)	59	63	83
103	M	2008	England	GAP	Sear et al. (2008)	59	81	83
104	M	2008	France	SYRAH-CE	Chandesris et al. (2008)	47	37	100
105	M	2008	Scotland	MImAS	UK Technical Advisory Group on the WFD (2008)	59	52	67
106	M	2009	Poland	RHQ	Wyżga et al. (2009)	65	56	83
107	M	2009	US	SAP	Starr (2009)	53	48	50
108	M	2009	US	SCS-RGA	Maine Department of Environmental Protection (2009)	65	22	50
109	M	2010	France	AURAH-CE	Valette et al. (2010)	41	18	17
110	M	2013	Italy	MQI	Rinaldi et al. (2013a, b, c)	65	59	83
111	HRA	1998	US	RVA	Richter et al. (1996)	32	54	n.a.
112	HRA	2000	US	HCA	Oregon Watershed Enhancement Board (2000)	36	41	n.a.
113	HRA	2005	Scotland	DHRAM	Black et al. (2005)	46	54	n.a.
114	HRA	2005	South Africa	HAI	Kleynhans et al. (2005)	39	41	n.a.
115	HRA	2006	Spain	QM-HIDRI	Munné et al. (2006)	39	18	n.a.
116	HRA	2006	US	HIT	Henriksen et al. (2006)	29	50	n.a.
117	HRA	2008	Taiwan	HMA	Shiau and Wu (2008)	46	54	n.a.
118	HRA	2009	US	IHA	The Nature Conservancy (2009)	25	59	n.a.
119	HRA	2010	Spain	IAHRIS	Martínez SM and Fernández Yuste (2010)	39	54	n.a.
120	HRA	2011	Italy	IARI	ISPRA (2011)	57	68	n.a.
121	HRA	2012	Australia	HS_RCI	Healey et al. (2012)	50	54	n.a.

Method are listed chronologically within each category: *PH* physical habitat assessment, *RH* riparian habitat assessment, *M* morphological assessment, *HRA* hydrological regime alteration assessment, *n.a.* not applicable

rather small-scale, localised interventions for habitat improvement. The introduction of the WFD marked a notable increase in the number of new methods developed in Europe, but most of these continued to be physical habitat surveys. Only in recent years, a significant increase in morphological and hydrological methods occurred, as a consequence of the increasing need to use catchment-wide and process-oriented approaches for implementing river restoration projects.

Methods for physical habitat assessment

This category includes methods and protocols for the survey, characterisation, and classification of physical habitat elements which can be described as river habitat surveys or physical habitat assessments (e.g., Platts et al. 1983; Plafkin et al. 1989; Raven et al. 1997; Ladson et al. 1999; National Environmental Research Institute 1999; LAWA 2000, 2002a, b). These focus mainly on instream habitats or microhabitats, but generally they also include some consideration of riparian habitats. Methods that aim to evaluate the overall functioning of the stream (e.g., method 39; Table 1) by including information on ecology-related features are also included in this category, although they are not strictly habitat survey methods. Seventy-three physical habitat assessment methods were identified, illustrating that this type of assessment remains the most common approach for assessing the hydromorphological state of a river (Table 1; Fig. 2).

Methods for riparian habitat assessment

Riparian zones are an integral component of riverine systems, since their lateral and vertical structures depend upon hydromorphological processes. However, the development of specific methods for assessing riparian conditions is relatively recent (Fig. 2). Some indicators of riparian conditions are often included in one of the other types of assessment methods, but this particular category consists of methods that are specifically designed for the characterisation of habitats in the riparian zone (e.g., Munné and Prat 1998), including some assessments of wetland

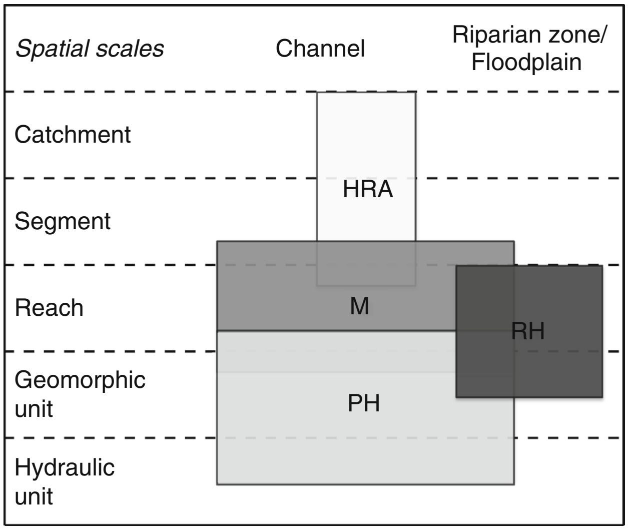


Fig. 1 Spatial context, spatial scales and overlap between assessment method categories. *PH* physical habitat assessment, *RH* riparian habitat assessment, *M* morphological assessment, *HRA* hydrological regime alteration assessment

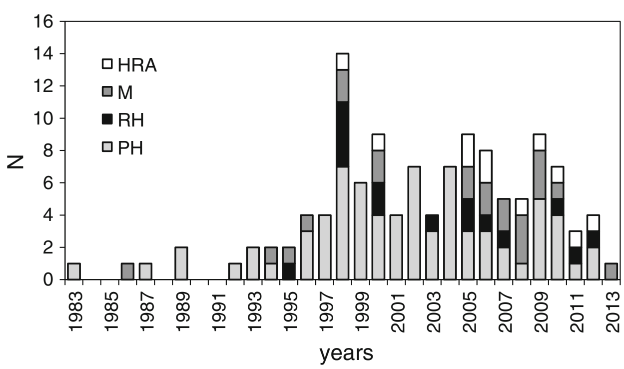


Fig. 2 Chronological appearance of hydromorphological assessment methods grouped into four categories

ecosystem functioning (methods 74, 78; Table 1). Fifteen riparian habitat methods were identified (Table 1).

Methods for morphological assessment

This category includes methods with the following distinctive characteristics differing from the category of physical habitat assessment: (1) they make a broader evaluation of river conditions including assessing channel forms, geomorphic adjustments, and human alterations; (2) the spatial scale is typically the 'reach' scale, i.e. a variable length with sufficiently homogeneous morphological characteristics and boundary conditions.

Following the development of physical habitat assessment methods, this type of broader assessment of river conditions has emerged, particularly during the last decade (Fig. 2). In this regard, Fryirs et al. (2008) suggest that a clear distinction should be made between a river audit and a river condition assessment. A river audit permits assessment of river status by generating information on the presence and frequency of physical habitats and their characteristics. A river condition assessment is a broader evaluation which places greater emphasis on physical processes, and aims to measure both pressure and response variables (i.e. hydromorphological and biological indicators) as a basis for developing a clearer understanding of the cause–effect relationships that regulate observed changes in system conditions. The 'morphological assessment' category contains methods that can be described as river condition assessments. A total of 22 methods were identified (Table 1).

Methods for the assessment of hydrological regime alteration

This category encompasses a further, independent, group of methods that produce hydrological assessments, particularly the development of specific indicators of hydrologic alteration (IHA) (method 118; Table 1; Richter et al. 1996; Poff et al. 2003), which can support assessments of the alteration of the natural hydrological regime. The output of these assessments is usually an index of the degree of deviation from unaltered conditions. As previously noted, the related environmental flows methods are not included in this review because their specific aim is an evaluation of flow requirements for aquatic ecosystems and species, rather than a direct assessment of the flow regime and its alterations (Arthington 1998; King et al. 2008; Poff and Zimmerman 2010). A total of 11 hydrological methods were identified (Table 1).

Methodology

Each method was analyzed, drawing mainly on information found in scientific papers and, where available, technical reports. In some cases, additional information was requested from authors or practitioners who were directly involved in the development or use of specific methods.

The type (category) of each assessment method was identified, and then (a) the characteristics of the method, (b) the features that were recorded, and, when appropriate, (c) the river processes that were assessed, were extracted. The types of extracted information are summarised in Table 2 (a more detailed description is reported in Rinaldi et al. 2013b). The way in which these three main types [(a)–(c)] of information were collected, differed slightly across the different assessment categories. In particular, information regarding the HRA methods differed from the first three categories (i.e., PH, RH, *M*):

Table 2 Information synthesis for each assessment category (PH, RH, M, HRA)

Categories of information	Type	Code	PH (73)	RH (15)	M (22)	HRA (11)
(a) Method characteristics			%			
Source of information/data collection methods	Map/remote sensing	M/RS	60	33	73	55
	Field survey or measurement	FS	99	93	91	9
	Rapid field assessment	RF	34	27	9	/
	Modelling	MO	10	0	5	91
	Existing database or data series	ED	/	/	/	100
Type of method/assessment	Characterisation/inventorying	CI	66	33	50	/
	Assessment by index	IN	78	73	59	/
	General assessment/design	GA	6	0	50	/
	Simple index	SI	/	/	/	36
	Multiple index	MI	/	/	/	46
	Modelling status	MS	/	/	/	18
	Expert judgment	EJ	/	/	/	27
River typology	No river typology	NT	/	/	/	64
	River typology/type	RT	/	/	/	0
Reference conditions	Use of reference conditions	RC	58	40	64	/
	Known reference conditions	KR	/	/	/	64
	Reconstructed reference conditions	RR	/	/	/	27
Spatial scale						
Longitudinal	Fixed length	FI	37	33	9	/
	Length vs. width	CW	18	7	14	/
	Variable length	VA	47	60	64	/
Lateral	Channel	CH	100	53	100	/
	Banks/riparian zone	B/RZ	95	93	96	/
	Floodplain	FP	71	53	86	/
	Catchment	CA	/	/	/	18
	River	RI	/	/	/	36
	Reach	RE	/	/	/	91
	Section	SE	/	/	/	36
Temporal scale	Present (last year)	P	100	100	100	/
	Recent (1–10 years)	R	3	7	36	/
	Historical (10–50 years)	H	6	7	46	/
	Monthly	M	/	/	/	55
	Daily	D	/	/	/	82
	Hourly	H	/	/	/	0
	Other	O	/	/	/	27
Predictive ability	Pressure change	PC	/	/	/	18
	Restoration success	RS	/	/	/	18
	No prediction	NO	/	/	/	27
Link to ecology	Link to ecology	LE	/	/	/	46
Strengths/gaps of the method	Easy to apply	EA	/	/	/	18
	Variable data series length	DL	/	/	/	18
	Gauged/ungauged stations	G/U	/	/	/	36
	A priori pressure assessment	AP	/	/	/	55

Table 2 continued

Categories of information	Type	Code	PH (73)	RH (15)	M (22)	HRA (11)
(b) Recorded features			%			
Channel features	Channel pattern	CP	55	13	82	/
	Channel form	CF	78	27	86	/
	Channel dimension	CD	84	33	73	/
	Flow type	FT	36	7	27	/
	Substrate	SB	85	20	82	/
	Physical parameters	PP	/	/	32	/
	In-channel vegetation	IV	62	20	27	/
	Woody debris	WD	62	27	50	/
	Artificial features and structures	AF	75	27	77	/
Banks/riparian zone features	Bank profile/shape	BP	66	27	82	/
	Bank material	BM	33	20	36	/
	Riparian vegetation structure	VS	71	93	64	/
	Riparian vegetation continuity	VC	52	67	32	/
	Riparian vegetation width	VW	38	53	27	/
	Species composition	SP	/	73	18	/
	Species coverage/distribution	SC	/	80	/	/
	Vegetation regeneration	VR	/	60	/	/
	Riparian soil	RS	/	20	/	/
	Artificial features and structures	AF	73	47	77	/
	Land use	LU	63	53	46	/
Floodplain features	Fluvial forms	FF	34	13	46	/
	Floodplain dimensions	FS	/	/	41	/
	Floodplain features	FD	/	/	32	/
	Land use	LU	67	40	46	/
Large scale characteristics	Large scale pressure	LS	49	13	68	/
	Hydrological regime/discharge	HR	70	27	82	/
	Valley form	VF	49	7	64	/
Hydrological conditions	Flow regime	FR	/	/	/	91
	Discharge	DI	/	/	/	91
	Change in depth	CD	/	/	/	9
	Velocity	VE	/	/	/	9
	Shear stress	SS	/	/	/	0
	Other	O	/	/	/	27
Metrics of flow regime	Magnitude	MG	/	/	/	73
	Frequency	FR	/	/	/	64
	Duration	DU	/	/	/	82
	Timing	TI	/	/	/	91
	Rate of change	RC	/	/	/	55
	Minimum flow	MI	/	/	/	82
	Maximum flow	MA	/	/	/	82
	Annual variability	AV	/	/	/	36
	Inter-annual variability	IV	/	/	/	46
	Intermittent flow	IF	/	/	/	9

Table 2 continued

Categories of information	Type	Code	PH (73)	RH (15)	M (22)	HRA (11)
Pressure assessed	Flow diversion	FD	/	/	/	73
	Groundwater interaction	GW	/	/	/	64
	Hydropeaking	HP	/	/	/	0
	Impoundment	IM	/	/	/	82
	Lateral/vertical adjustment	CA	/	/	/	0
	Large scale pressure	LS	/	/	/	36
(c) River processes			%			
River processes	Longitudinal continuity	LC	56	7	55	/
	Lateral continuity	TC	49	40	68	/
	Large scale sediment connectivity	SC	/	/	36	/
	Bank erosion/stability	BE	59	27	82	/
	Channel adjustments	CA	12	7	82	/
	Vertical connection (groundwater)	GW	/	/	18	/

For each category the percentage of methods considering a specific type of characteristic, feature and process is given. Codes in the third column correspond to those reported in Figs. 3 and 4. "/" not analysed

(a) Method characteristics. These concerned data collection methods or sources (e.g., field survey, remote sensing, etc.); the type of method (e.g., qualitative characterisation, assessment by a quantitative index); whether the method makes use of some type of reference conditions; the spatial scale of the assessment, including the zones of the river corridor that were surveyed; and the temporal scales of investigation. There are several approaches used to define reference conditions, including: (1) empirical data from reference sites; (2) historical information (i.e. some historical state is assumed as a reference condition); (3) modelled reference; (4) theoretical reference; (5) based on expert judgement; (6) based on the historic range of variability or evolutionary sequence and ergodic reasoning (Brierley and Fryirs 2005). For hydrological assessment methods, additional information was collected concerning the predictive ability of the assessment, whether methods make a direct link to ecology, and the particular strengths of a method (i.e., ease of application, ability to use variable data series lengths, ability to be applied both to gauged and ungauged catchments, inclusion of an assessment of pressures a priori).

(b) Recorded features. These represent the core of the review, since they highlight differences between the categories of assessment. In the case of physical habitat, riparian habitat, and morphological assessment, they comprise lists of hydromorphological features recorded in various portions of the river corridor (instream, banks, riparian areas, floodplain). For the hydrological assessment methods, these include metrics of hydrological characterisation, alteration and pressures.

(c) River processes. These are only relevant to the first three categories of assessment, and provide information on whether any specific physical river process is included in the evaluation (e.g., longitudinal, lateral and vertical continuity, bank processes, channel adjustments).

A comparative analysis of hydromorphological assessment methods

Based upon the characteristics, information, and, where relevant, river processes incorporated within each assessment, the following sections provide a summary of the properties of the assessment methods within each of the four categories (physical habitat, riparian habitat, morphological, hydrological regime alteration).

The percentage of methods within each category covering the different characteristics, recorded features and river processes is summarised in Table 2; Figs. 3 and 4.

Methods for physical habitat assessment

Most physical habitat assessments are based on extensive field surveys. Maps and remote sensing techniques are also frequently used for preliminary reconnaissance of the river and to allow for reach delineation.

Seventy-eight percent of physical habitat assessment methods generate one or more indices that evaluate hydromorphological condition. These indices are usually derived from the inventory of recorded features (e.g., 12, 31; note numbers refer to methods listed in Table 1), although some methods also aim at evaluating the overall functioning of the stream (6 % of methods) by including information on ecology-related features (e.g., method 39; Table 1). Some form of reference conditions are also explicitly incorporated in 58 % of the reviewed methods.

The spatial scale of most physical habitat assessments is rather small, coinciding with what might be described as a site scale, i.e. a river length in the order of a few 100 m. The longitudinal length of each site or reach may be either fixed (e.g., 500 m) or variable, in the latter case the length reflects larger-scale characteristics (e.g., geology and climate, presence of longitudinal discontinuities, etc.). All reviewed methods focus on the channel; most include the river banks and riparian areas; but <75 % extend to the surrounding floodplain. Concerning their temporal scale, all reviewed methods assess the present state of the river at the time of survey, while very few include information on recent or historical river conditions (45; Table 1).

Channel features usually include channel dimensions, dominant bed sediment size and composition, channel forms and geomorphic units (e.g., number of riffles and pools), and artificial features (e.g., dams, weirs, culverts, deflectors, etc.). The physical structure of the banks and the presence of artificial elements are the most commonly recorded features of riverbanks and riparian zones. Land use and the presence of fluvial forms (e.g., oxbow lakes, wetlands) are the most commonly recorded floodplain features. Information on large-scale catchment and valley characteristics is rarely included, and hydrological information is only provided to characterize the condition at the time of the survey (e.g., estimation of discharge). However, in some countries (e.g., Australia), the hydrological assessment is more detailed and considers several properties of the river regime (e.g., Ladson et al. 1999; Parsons et al. 2004).

In relation to river processes, longitudinal and lateral continuity are often assessed based on the presence of artificial features, while only 12 % of methods include some consideration of channel adjustments (i.e. widening/narrowing, aggradation/degradation).

Methods for riparian habitat assessment

As for physical habitats, the assessment of riparian habitats is mainly undertaken using extensive field assessment protocols, while the use of maps and remote sensing is rare (Fig. 3; Table 2; but see method 87, Table 1).

The assessment approach varies, ranging from the use of indices or quality classes to the application of inventory protocols often including sampling of vegetation community composition (e.g., 75, 84; Table 1). A relatively low proportion (40 %) of the methods makes explicit use of reference conditions (e.g., 87; Table 1).

Riparian habitat assessment is usually undertaken at the reach scale, which is larger than the site scale that is generally employed in river habitat assessments. The area or length that is surveyed is variable and has relatively homogenous vegetation characteristics. Similar to physical habitat assessment, the temporal scale of investigation is restricted to the time of the survey.

In terms of the recorded features, these methods focus on banks and riparian zones. About 50 % of the investigated methods record channel features, and mainly focus on the width of the channel in relation to vegetated areas such as islands and vegetated bars, and artificial features. The vegetation features most commonly assessed include vegetation structure, species coverage, and species composition, with a special emphasis on the presence and abundance of non-native species (particularly in European methods). Some methods place emphasis on the temporal dynamics of vegetation pattern (i.e. evidence of vegetation regeneration, for example, in terms of the presence of seedlings).

Most of the methods evaluate longitudinal and lateral vegetation continuity which provides insights into the lateral connectivity between the riparian area and its river and floodplain. Only a small proportion attempts to relate the riparian habitat to physical processes.

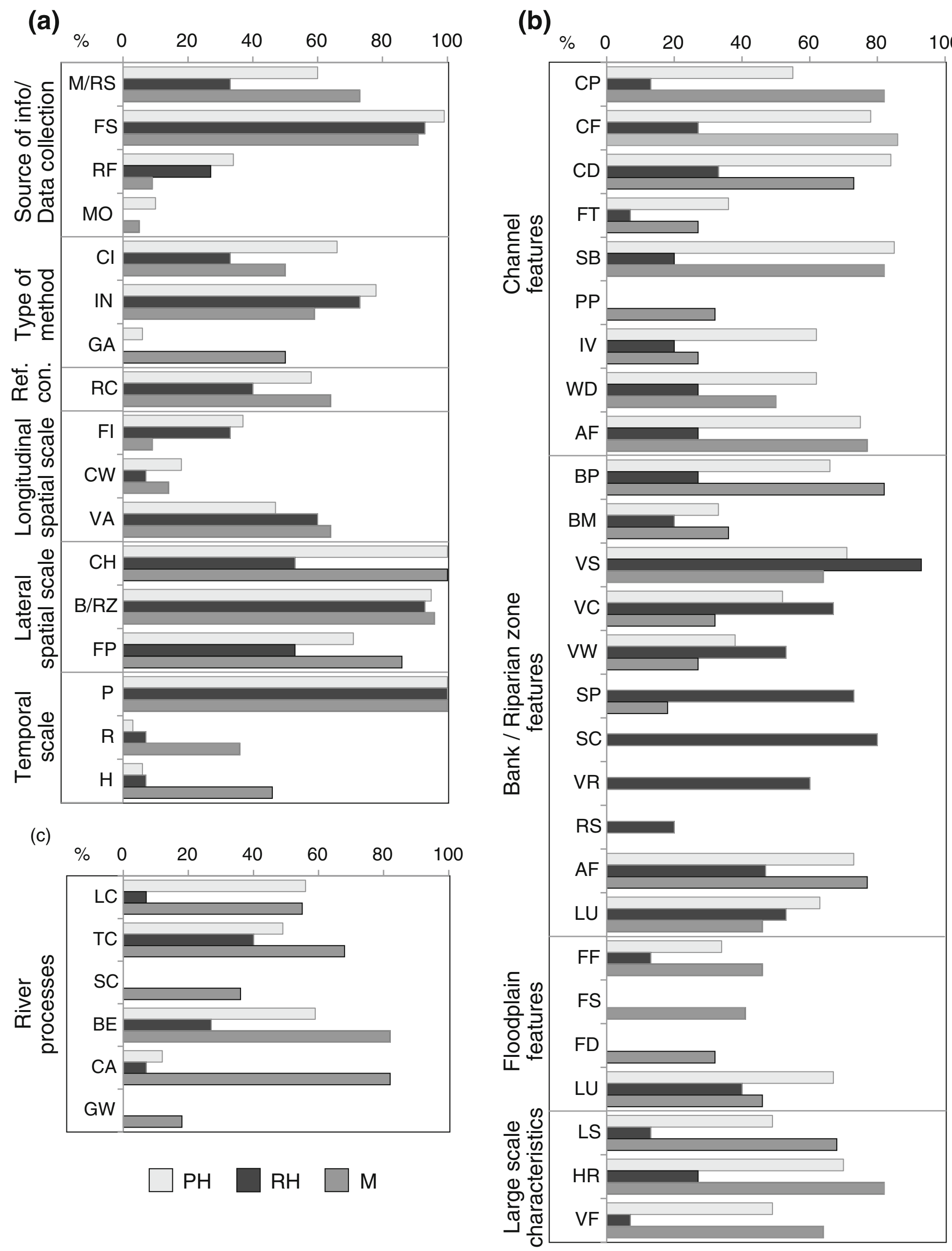
Methods for morphological assessment

As for the previous categories, field survey is the predominant method of data-gathering, but morphological assessments make more extensive use of remote sensing data and maps (73 %, Fig. 3; Table 2).

Morphological methods are mainly used for: (1) an evaluation framework of river conditions (e.g., 97, 103; Table 1); (2) an assessment supported by one or more indices (e.g., 102, 110; Table 1); or (3) an assessment directed towards restoration design (e.g., 92; Table 1). Some methods provide a risk assessment of existing pressures rather than an analysis of morphological conditions (e.g., 104; Table 1). In some cases, the assessment provides a morphological characterisation that is included in broader protocols for evaluating the river or watershed conditions (e.g., 96, 99; Table 1). Lastly, some morphological methods are used in combination with the assessment of other ecosystem components to provide an evaluation of the overall river conditions (Healey et al. 2012). 64 % of methods include the use of reference conditions.

Compared to the previous categories, morphological assessment is generally carried out at a larger spatial scale, which could still be termed the reach scale, i.e. a length in the order of a few km with sufficiently homogeneous

Fig. 3 Analysis of **a** method characteristics, **b** recorded features, **c** processes incorporated in the reviewed physical habitat (PH), riparian habitat (RH), and morphological (M) assessment methods. For abbreviations see Table 2



morphological characteristics and boundary conditions. In most cases (>80 %), the assessment concerns the entire river corridor (i.e. channel, banks, riparian zones, and floodplain). In a temporal context, a larger proportion of these methods take account of recent and historical channel adjustments through the use of maps and remote sensing.

Compared to physical habitat methods, the assessment of channel features is more focussed on channel pattern and physical variables, but less on the survey of instream habitats (e.g. instream vegetation, large wood accumulations, flow types). Although some characterisation of bed sediment is incorporated within most methods, relatively few methods attempt to evaluate substrate structure alterations such as armouring and clogging (or embeddedness) (see methods 105, 109, 110; Table 1). Bank morphology, artificial features in the riparian zone, and floodplain forms and features are considered to some extent by most of the morphological methods. More than 80 % evaluate hydrological alterations, although usually only in qualitative terms.

Many also include some consideration of river processes, including sediment transport (for continuity), bank erosion, and channel adjustments.

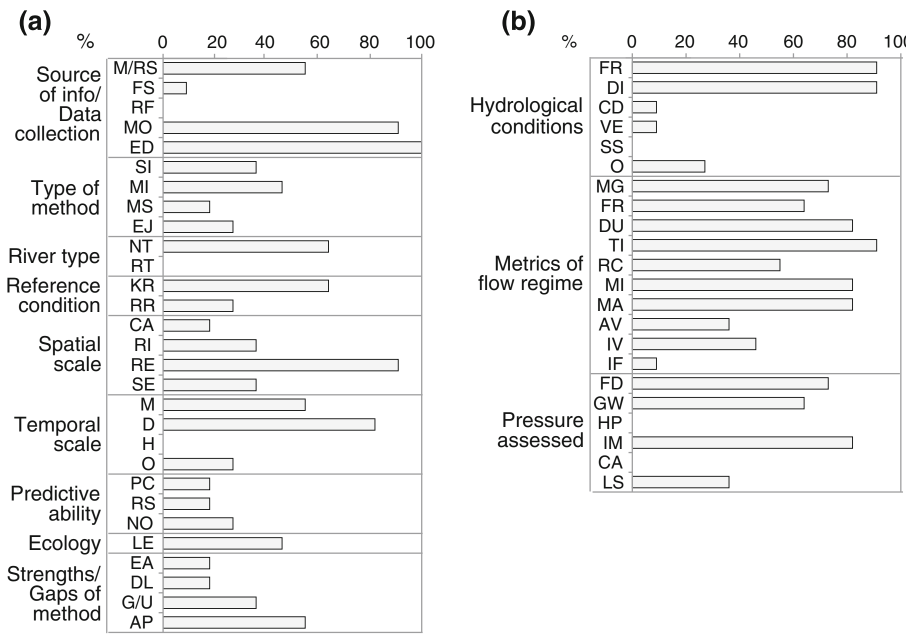


Fig. 4 Analysis of **a** method characteristics, **b** recorded features incorporated in the reviewed methods of assessment of hydrological regime alteration (HRA). For abbreviations see Table 2

Methods for the assessment of hydrological regime alteration

The main characteristics of this category of assessment are summarised in Fig. 4 and Table 2.

This type of assessment mainly involves the processing of existing hydrological data series or the use of modelled data. Numerical models are required when data are not available or to fill gaps in incomplete data series (e.g., 120; Table 1). Maps and remote sensing can be used to support the evaluation of human pressures at the catchment scale or for characterising the river or catchment (50 % of methods). Field measurements of river discharge may be included in the assessment (e.g., 115; Table 1), particularly for ungauged reaches (e.g., 120; Table 1).

Most of the methods produce a final single index or multiple indices. Given their predictive ability, some are used to build scenarios for evaluating the success of restoration or the impact of specific river changes (e.g., 117; Table 1). Reference conditions are often used, and consist of undisturbed or pre-impact conditions based on existing data or on modelling results (64 and 27 %, respectively).

The spatial scale of application varies widely from the reach (the most common scale) to the segment (i.e. a macro-reach of tens of km) or to the entire catchment.

Forty-six percent of methods link explicitly with ecological components. For example they may assess the ecological response to changes in the hydrological regime in order to evaluate the present ecological status (114; Table 1).

Concerning the recorded features, almost all make use of river discharge data. In the cases where field data are required, cross-sections, flow velocity and depth are generally measured (e.g., 115; Table 1). Some methods (e.g., 112; Table 1) also combine watershed land use characteristics (e.g., coverage, density) with hydrological data. Almost all are based on the five main components of the flow regime: discharge magnitude, frequency, duration, timing, rate of change (Richter et al. 1996; Poff et al. 2003). Some also evaluate temporal variability (i.e., annual/seasonal, inter-annual/climatic changes) (e.g., 116; Table 1).

In terms of assessed pressures, the effects of impoundments, water abstractions and diversions are commonly evaluated, while none of the reviewed methods assess the effects of hydro-peaking from power generation plants.

Strengths, limitations and gaps in assessments

Based on the above review of existing assessment techniques, this section identifies strengths and limitations within each of the four categories (Table 3). This is supplemented by the authors' expert opinion on the pros and cons of the methods implemented and applied by EU countries within the context of the WFD.

Methods for physical habitat assessment

These methods have a number of strengths. They provide a framework within which habitat units can be efficiently inventoried and sampled, and so they are useful for characterising the range of physical habitats that are present, their heterogeneity and the contemporary physical structure of ecosystems. Additionally, these methods often inventory some features of ecological relevance, which are not addressed within the other categories, such as the presence of refuge areas, organic matter, shading, etc. (e.g., 12, 40; Table 1). Therefore, they are potentially helpful in establishing links between morphology and ecological conditions and communities (e.g., supporting explanation of the distribution patterns of organisms, the composition and structure of biological communities or aspects of ecosystem functioning). Finally, some of these methods have been used quite widely across Europe (e.g., method 12, Table 1, and similar procedures developed in other countries), allowing comparison of data and results from different regions.

Nevertheless, physical habitat assessments have several shortcomings. First, these methods have long been considered to be equivalent to hydromorphological assessment, but they are now recognised to represent only one component of a hydromorphological evaluation, which is mainly the occurrence of habitats. Indeed, when physical habitat methods are used with the aim of understanding physical processes and causes of river alterations, they generally fail (e.g. Fryirs et al. 2008; Entwistle et al. 2011).

More specifically, the spatial scale of investigation (i.e., the site scale of a few 100 m) is usually inadequate for the accurate diagnosis and interpretation of the causes of any morphological alteration. This is because physical site conditions commonly originate from processes and causes that operate at larger spatial scales (e.g., Frissel et al. 1986; Brierley and Fryirs 2005).

Additionally, physical habitat assessment methods require very detailed site-specific data collection, such that their application to large numbers of water bodies may be impractical. These methods also make limited use of geomorphological approaches other than field surveys (Table 2; Fig. 3). The expansion of these assessments to incorporate remotely sensed data and GIS analysis would permit wider spatial and temporal scales of analysis, and more informative assessments. As a consequence, observations tend to be viewed in a static way, rather than placing them in the temporal context within which channel processes operate and river channels adjust. This primary limitation prevents the development of a sound understanding of hydromorphological responses to pressures (i.e. cause–effect relationships), which is essential for identifying and subsequently implementing appropriate rehabilitation actions (Kondolf et al. 2003; Fryirs et al. 2008).

The use of reference conditions based on statistical analyses of empirical data is also questionable. Selection of a sufficient and representative number of reference sites can be problematic, given that many different morphological typologies should be represented. The choice of natural sites is also prone to errors, because sites without artificial elements could still be morphologically altered by disturbances occurring in other parts of the river network (upstream or downstream) or that may have occurred in the past. Moreover, these procedures tend to identify high

Table 3 Summary of strengths and limitations for each method category

	Strengths	Limitations
PH	1. Framework for habitat inventory	1. Small and usually fixed spatial scale
	2. Ecological relevance	2. Detailed, time-consuming data collection
	3. Widely used	3. Limited use of geomorphological methods and remote sensing
		4. Static approach
		5. Local assessment of 'natural' state, which corresponds to feature presence/absence
		7. Outdated terminology and incomplete coverage of geomorphic units (and channel patterns)
RH	1. Focus on riparian zone and vegetation	1. Limited consideration of processes
	2. Recent development of hymo integrating approaches (e.g., remote sensing, reach scale)	2. Poorly developed/used (e.g., mainly in the Mediterranean areas of EU)
	3. Including strengths of PH	Additional limitations, as for PH methods
M	1. Robust geomorphological-based approach	1. Physical processes difficult to assess rigorously
	2. Use of geomorphologically-meaningful spatial scale (i.e., reach)	2. Temporal component difficult to assess
	3. Account for temporal component	3. Several definitions of reference state
		4. Assessment of vertical continuity not explicitly included
		5. Limited consideration of physical habitats
		6. Lack of linkages with biological components
HRA	1. Robust approaches (indicators)	1. Need for a large dataset and long-time series
		2. Difficult to define unaltered hydrological regime
		3. Short time scales not included (e.g., hydropeaking)
		4. Groundwater alteration not included

status conditions with maximum morphological diversity for all types of rivers, failing to recognize that in some cases the natural geomorphic structure of a particular stream type may be very simple whereas in other cases it may be more complex (Barquín et al. 2011; Fryirs 2003).

Additional limitations can be identified in the way that physical habitat methods characterize channel forms and geomorphic units. These concern a notable gap in the terminology used to describe geomorphic units in most habitat surveys when compared to the present state of the art in fluvial geomorphology. For example, most refer only to riffles and pools when describing the configuration of the river bed, probably because most habitat survey methods have been developed to address small, single-thread, sand-bed or gravel-bed rivers. As a result, there is incomplete consideration, for example, of the wide variety of bed morphologies found in steep, mountain, cobble- or boulder-bed streams, where other geomorphic units may occur (cascades, rapids, glides, step-pools, etc.). Although considerable progress has been made recently in the description and terminology associated with geomorphic units found in mountain streams (e.g., Halwas and Church 2002; Comiti and Mao 2012), this post-dates the development of most physical habitat assessment methods, and this progress has been insufficiently incorporated by updating these methods. The variety of bed morphologies found in large lowland rivers is also poorly incorporated (e.g., dune-ripple morphologies). Similarly, geomorphic units found in rivers with complex, transitional or multi-thread patterns (i.e., wandering or braided) are not adequately covered, although some effort has been made recently to represent some of these morphologies (including ephemeral or temporary streams typical of some Mediterranean regions in Southern Europe; e.g., 54, Table 1). In the case of large rivers with complex morphologies (e.g., many piedmont Alpine rivers), field surveys alone are inadequate to characterize channel forms and geomorphic units, and so the incorporation of remote sensing techniques is essential. Furthermore, considerable progress has been achieved recently in developing new procedures whereby the identification and analysis of individual landforms (geomorphic units) is set in a more appropriate spatio-temporal framework (e.g., Fryirs and Brierley 2013; Brierley et al. 2013), but this type of approach has not been incorporated into any of the analysed methods.

Methods for riparian habitat assessment

Many of the strengths and shortcomings of physical habitat assessments also apply to riparian habitat assessments since they usually adopt a similar approach. However, riparian habitat assessments also have some specific strengths, since they integrate well with physical habitat assessments by extending their coverage from the river channel into the riparian zone, and also giving more emphasis to vegetation, particularly riparian vegetation. Therefore, they are extremely important in accomplishing a requirement of the WFD, which is to give consideration to vegetation as a key biological as well as hydromorphological element.

While most of these methods are based on field survey and some are still focussed on the site scale, others methods make use of other information sources and approaches (e.g., integrated use of remote sensing and field survey) and a larger spatial scale (reach) that can be integrated with other hydromorphological methods allowing an overall river condition assessment (e.g., 87; Table 1).

Despite these specific strengths, many riparian habitat assessments are essentially an inventory of habitats and vegetation conditions observed along a portion of river. As a result, there is limited consideration of the processes generating riparian conditions and the causes of alteration at larger spatial and temporal scales.

This type of assessment is not widely used yet. In the US, riparian assessment is often coupled with the assessment of wetland ecosystem functioning (e.g., 78; Table 1). In Europe, most methods have been developed in Mediterranean countries (e.g., Spain, Italy), where flashy flow regimes and ephemeral, multi-channel patterns (incorporating vegetated islands) are more frequent, determining a more complex riparian forest structure. This regional bias means that the validity of many of the techniques is uncertain if they were to be applied to other climatic, hydrological and morphological conditions. Additionally a regional bias could also exist in terms of human impacts (e.g., the predominance of water abstraction and sediment budget changes in southern European countries in comparison with the predominance of vegetation management/removal and pollution in northern ones).

Methods for morphological assessment

Compared to the previous two categories, these methods make use of a more robust, geomorphologically based approach by integrating information drawn from remote sensing and field survey, with a stronger consideration of physical processes at appropriate spatial and temporal scales. Such an approach goes beyond an inventory of forms to support the development of a better understanding of cause–effect relationships.

In most cases the basic spatial unit for the application is the *reach* scale, commonly a few km in length, where reaches are identified in a geomorphologically meaningful way, as sections of river along which present boundary conditions are relatively uniform.

Additionally, some methods account explicitly for the temporal component by incorporating a historical analysis of channel adjustments to provide insights into the timing and causes of alterations and into potential future geomorphic changes (e.g., 110; Table 1). Understanding evolutionary trajectories and past changes is an important component when assessing contemporary river conditions. Morphological indicators should take account of how rivers have changed through time (Brierley and Fryirs 2005; Fryirs et al. 2008).

Some of these strengths could also be interpreted to some degree as limitations. Physical processes are generally more difficult to assess than a simple inventory of existing forms. A rigorous evaluation of processes requires the collection of measurements at different times and process rates (e.g., bank erosion or deposition), quantitative modelling or analyses of changes in the process regime (e.g., alterations in sediment transport or water discharge regime), all of which are unlikely to be feasible within the context of a relatively rapid hydromorphological assessment. For practical reasons, recorded indicators of processes are thus often generated from a static visual assessment of the occurrence or not of active processes (observed in the field or based on remotely sensed information). In other cases, the evaluation is indirectly based on the presence of artificial elements, which are inferred to have significant impacts on some processes. For example, the simple presence of transverse structures is often assumed to alter sediment fluxes and continuity, without any quantitative evaluation of the magnitude of their effects. Even though some morphological assessment methods explicitly account for the temporal component by considering channel adjustments (i.e. changes of channel form through time), this analysis is often prone to errors because, it is difficult and requires specialist expertise, specific analyses (e.g., GIS analysis of channel planimetric changes), as well as high spatial and temporal resolution data. The definition of a reference state for morphological conditions is even more problematic than for the other categories. Some morphological assessments implicitly incorporate the assumption that the past state is a reference condition. However, where a more rigorous approach is attempted, a common vision of reference conditions is lacking (Bertoldi et al. 2009; Dufour and Piégay 2009; Rinaldi et al. 2013a), leading to the application of non-harmonised definitions of reference conditions.

The focus of morphological assessments is generally on fluvial forms and processes at wider spatial and temporal scales than physical habitat assessment, but the vertical component of river continuity (i.e., the connection to groundwater) is still poorly considered (Table 2; Fig. 3). Limited attention is also given to a systematic inventory of the geomorphic units and assemblages that characterize a given morphology and are useful for ecosystem characterisation. The latter can be a severe limitation when morphological assessment is used alone.

Lastly, these methods evaluate morphological conditions exclusively in terms of physical forms or processes, without any inferences concerning their consequences or implications in terms of ecological state. This means that a high morphological quality is not necessarily related to a good ecological state, although this is most likely the case, since many authors suggest that functioning of physical processes and dynamic equilibrium promote ecosystem diversity and functioning (e.g., habitat heterogeneity; Tockner and Ward 1999; Rinaldi et al. 2013a). However, a clear relation between some of the morphological indicators used in these methods and biological responses is currently lacking.

Methods for the assessment of hydrological regime alteration

The main strength of this category of assessment is that it makes use of well-defined indicators based on quantitative assessments, statistical analyses or physics-based models. For example, most methods employed within Europe are based on some or all of the IHA proposed by Richter et al. (1996) and Poff et al. (2003).

The drawback is that such indicators and models generally require large data sets and long-time series, which are often not available. In particular, applying these methods to ungauged streams is problematic. If models are applied when data are not available or incomplete, the uncertainties that can affect the estimation should be carefully considered.

A further critical issue is defining the unaltered (natural) reference hydrological regime. This requires a sufficiently long, mostly non-existing data series from pre-impact conditions. Assuming that 'pre-impact' data series related to a particular intervention (e.g., dam construction) represent natural conditions is rarely appropriate, particularly in Europe where river systems and their hydrological regime have been affected over many centuries by numerous and continuing alterations at a catchment scale (Rinaldi et al. 2013c).

IHA are usually based, at best, on daily discharges. This prevents the analysis of hydrological alterations that occur at shorter time scales, such as hydropeaking (as well as thermopeaking), that have very important effects on ecological communities (e.g., Paetzold et al. 2008; Person and Peter 2012). Specific indicators or models for analysing hydropeaking are needed. Recent progress has been made to develop integrating approaches and key indicators to assess hydrological alterations due to hydropower impacts (e.g., Zolezzi et al. 2009; Meile et al. 2011). These should be incorporated to further improve hydrological assessment methods.

Like other categories, the effects of groundwater alterations are generally not included apart from an indirect assessment through low-flow analyses. Groundwater systems are an important component of riverine ecosystems and methods are needed to incorporate them into assessments in a more detailed way.

Because of the above limitations, the practical use of these methods for supporting hydromorphological assessment is still modest. An alternative and more feasible approach might be an analysis of existing hydrological pressures, based on the presence and type of impacts and causes of alteration (e.g., 112, 121; Table 1). However, it can be extremely difficult to correctly evaluate the effects of a given pressure in the absence of a quantitative analysis of hydrological data. Merging of these two types of approach has been achieved in relation to developing environmental flow methods, but with the aim of defining flow requirements for the proper biological functioning together with the human needs (e.g., Arthington 1998; King et al. 2008), rather than to assess regime alteration alone.

Methods implemented by EU countries in the context of the WFD

Finally, specific focus has been put on the methods which have been formally approved or are commonly used (but without formal approval) by European countries to implement the WFD, because the choice of the methods and the outcome of the assessments strongly influences decision-making on ecological status and the need for rehabilitation programmes. A more detailed analysis of these methods is provided by Rinaldi et al. (2013b). Each method is included in one of the previously defined categories (Fig. 5a), revealing that physical habitat assessment methods prevail (31, 37, 38, 40, 44, 54, 60, 61, 64, 65, 68, 70, 73, 77; Table 1), followed by morphological methods (101, 104, 105, 109, 110; Table 1), while the use of riparian habitat and hydrological alteration methods is very limited (77 and 120, respectively; Table 1). For this analysis, an adaptation of RHS to Portugal (Raven et al. 2009; Ferreira et al. 2011) has also been included within the physical habitat assessment methods, while the three different versions of the German method have been counted only once (the overall LAWA, corresponding to methods 31, 37, and 38 in Table 1).

In most EU countries (with the exception of France and Italy) physical habitat assessments are the only methods used for the hydromorphological assessment in the context of the WFD. The limitations of each category of methods have been previously discussed, but the following points summarise current general limitations in the application of hydromorphological assessment methods within the EU:

1. A lack of consideration of physical processes is the most important omission in currently used hydromorphological assessment methods. This omission limits development of a proper understanding of the causes of alterations and responses to them (i.e. cause–effect). Such an understanding is essential, if appropriate rehabilitation actions are to be implemented (Kondolf et al. 2003; Fryirs et al. 2008).
2. Although informative, physical habitat assessment is only one component of an overall hydromorphological assessment. At present, few EU countries attempt to incorporate other components into a fully integrated hydromorphological assessment.
3. There is also currently no integration of the physical (hydromorphological) aspects with other components (i.e. water quality, biology, ecology) to give a genuinely interdisciplinary approach to overall river condition assessment (Fryirs et al. 2008).
4. For future hydromorphological assessment and monitoring, a more integrated use of more components is required to achieve an overall assessment, and a stronger emphasis within hydromorphology on morphological and hydrological methods would be beneficial.

To place these EU WFD-related assessments into a broader context and allow a more general comparison of

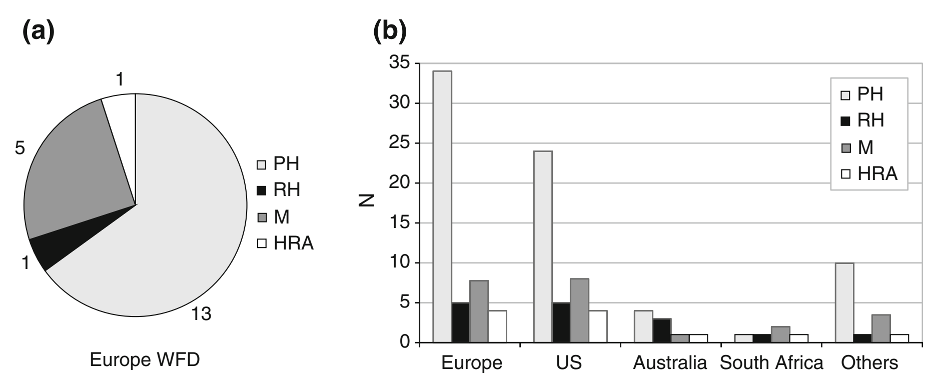


Fig. 5 Number of reviewed methods, sub-divided according to the assessment category, used by: **a** European countries for the implementation of the Water Framework Directive; **b** European (in general, not only for the WFD) and non-EU countries, where "others" refers to Canada, China, New Zeeland, Switzerland, Ukraine

the use of the four categories of methods worldwide, the distribution of method categories including all European methods (i.e. not only those implemented for the WFD) as well as other non-European methods is plotted in Fig. 5b. It confirms that the most widely used category of methods worldwide is the physical habitat assessment, followed by a recent increase in the development and application of more morphological methods. Exceptions are South Africa, where morphological assessments prevail, and Australia, where it seems that more interest is allocated to riparian habitats.

Concluding remarks and recommendations for future developments

Our analysis of hydromorphological assessment methods has built upon and extended existing reviews (Raven et al. 2002; Mc Ginnity et al. 2005; Weiss et al. 2008; Fernández et al. 2011) providing the following new insights.

Most previous reviews have a specific focus on European methods (e.g., Raven et al. 2002; Weiss et al. 2008), mainly aiming to support suitable method selection for WFD implementation. This paper started from a wider geographical perspective (similar to Fernández et al. 2011), and subsequently focussed briefly on European WFD-related assessments.

Earlier reviews focussed on physical habitat assessment often seen to be synonymous with hydromorphological assessment. This paper reviewed additionally three other assessment categories to identify the strengths and limitations of various approaches resulting in recommendations to further progress this area of assessment.

Acknowledging the identified limitations and gaps, future developments need to incorporate physical processes into hydromorphological assessment methods. This aspect is particular relevant for the more dynamic rivers with short- to mid-term habitat turnover. This can be achieved by a wider application of morphological methods to increase the capability to assess geomorphic processes rather than just physical habitat assessment. This asks for a spatio-temporal hierarchical framework with relevant units and scales, key factors and appropriate indicators to assess morphological processes and alterations.

Finally, we thus recommend developing a framework for integrated hydromorphological analysis, where the morphological and hydrological components (including vegetation as a morphological driver) are key parts to evaluate and classify hydromorphological state and quality. Moreover, to better diagnose the status of rivers and give guidance for improvement it is important to better tune this with assessment of other components, such as water quality, and ecology. In this respect, it is worth recalling that the various methodological categories reflect different conceptual approaches and disciplines (e.g., hydrology, geomorphology, biology), and that application of each specific approach requires training and background knowledge of the underlying principles. Application without the necessary background and skills could seriously limit adopting a truly integrated analysis of river ecosystems.

Acknowledgments The work leading to this paper has received funding for the EU's FP7 under Grant Agreement No. 282656 (REFORM). W. Bertoldi and W. Van de Bund are acknowledged for their inputs and comments. The REFORM colleagues are acknowledged for providing information on the methods adopted for WFD implementation: N. Friberg, G. Geerling, M. Gielczewski, M. Gonzales del Tanago, A. Henshaw, J. Kail, B. Lastoria, S. Mariani, A. Marzin, S. Muhar, P. Pollard (REFORM Advisory Board), M.C. Perez, P. Reichert, L. Sandin, J. Segersten, M. Staras, C. Wolter.

References

Agences de ĹEau (1998) SEQ physique. A system for the evaluation of the physical quality of watercourses. Version 0. Angers. In: Mc Ginnity PM, Mills P, Roche W, Müller M (eds) A desk study to determine a methodology for the monitoring of the 'morphological conditions' of Irish Rivers. Final report. Environmental RTDI Programme 2000–2006. Central Fisheries Board—Compass Informatics—EPA

Anderson JR (1993) State of the rivers project. Department of Primary Industries, Queensland. In: Mc Ginnity PM, Mills P, Roche W, Müller M (eds) A desk study to determine a methodology for the monitoring of the 'morphological conditions' of Irish Rivers. Final report. Environmental RTDI Programme 2000–2006. Central Fisheries Board—Compass Informatics—EPA

Arthington AH (1998) Comparative evaluation of environmental flow assessment techniques: review of holistic methodologies. LWRRDC Occasional Paper 26/98. ISBN 0 642 26745 6

Barbour MT, Gerritsen J, Snyder BD, Stribling JB (1999) Rapid bioassessment protocols for use in streams and wadeable rivers: periphyton, benthic macroinvertebrates, and fish, 2nd edn. EPA 841-B-99-002 U.S

Barquín J, Fernández D, Álvarez M, Peñas F (2011) Riparian quality and habitat heterogeneity assessment in Cantabrian rivers. Limnetica 30(2):329–346

Bertoldi W, Gurnell A, Surian N, Tockner K, Zanoni L, Ziliani L, Zolezzi G (2009) Understanding reference processes: Linkages between river flows, sediment dynamics and vegetated landforms along the Tagliamento River, Italy. River Res Appl 25:501–516. doi:10.1002/rra.1233

Black AR, Bragg OM, Duck RW, Rowan JS (2005) DHRAM: a method for classifying river flow regime alterations for the EC Water Framework Directive. Aquat Conserv Mar Freshw Ecosyst 15:427–446

Braioni MG, Penna G (1998) I nuovi Indici Ambientali sintetici di valutazione della qualità delle rive e delle aree riparie: wild State Index, Buffer Strip Index, Environmental Landscape Indices: il metodo. Biologia ambientale 6:3–38

Brierley GJ, Fryirs KA (2005) Geomorphology and river management: applications of the river style framework. Blackwell, Oxford

Brierley GJ, Fryirs K, Cullum C, Tadaki M, Huang HQ, Blue B (2013) Reading the landscape: integrating the theory and

practice of geomorphology to develop place-based understandings of river systems. Prog Phys Geogr 37(5):601–621
Buffagni A, Erba S, Ciampitiello M (2005) Il rilevamento idromorfologici e degli habitat fluviali nel contesto della direttiva europea sulle acque (WFD): principi e schede di applicazione del metodo Caravaggio. Istituto di Ricerca sulle Acque. CNR IRSA. Notiziario dei metodi analitici 2:32–34
Buhmann D, Hutter G (1996) Fließgewässer in Vorarlberg. Gewässerstrukturen Erfassen - Bewerten - Darstellen. Ein Konzept. Schriftenreihe Lebensraum Vorarlberg, Band 33. In: Mc Ginnity PM, Mills P, Roche W, Müller M (eds) A desk study to determine a methodology for the monitoring of the ‘morphological conditions’ of Irish Rivers. Final report. Environmental RTDI Programme 2000–2006. Central Fisheries Board—Compass Informatics—EPA
Bundesamt für Umwelt, Wald und Landwirtschaft (BUWAL) (1998) Methoden zur Untersuchung und Beurteilung der Fließgewässer. In: Mc Ginnity PM, Mills P, Roche W, Müller M (eds) A desk study to determine a methodology for the monitoring of the ‘morphological conditions’ of Irish Rivers. Final report. Environmental RTDI Programme 2000–2006. Central Fisheries Board—Compass Informatics—EPA
Bundesanstalt für Gewässerkunde (2001) Strukturgüte-Kartierverfahren für Wasserstraßen. In: National Environmental Research Institute and Slovak Hydrometeorological Institute (2004) Establishment of the protocol on monitoring and assessment of the hydromorphological elements (Slovakia). Final report
CEN (2002) A guidance standard for assessing the hydromorphological features of rivers. CEN TC 230/WG 2/TG 5:N32
Chandesris A, Mengin N, Malavoi JR, Souchon Y, Pella H, Wasson JG (2008) Système Relationnel d’Audit de l’Hydromorphologie des Cours d’Eau. Principes et methodes, v3.1. Cemagref, Lyon
Comiti F, Mao L (2012) Recent advances in the dynamics of steep channels. In: Church M, Biron PM, Roy AG (eds) Gravel-bed Rivers: processes, tools, environments. Wiley, New York, pp 353–377
Crowe E, Kudray G (2003) Wetland assessment of the Whitewater watershed. Report to US Bureau of Land Management, Malta Field Office. Montana Natural Heritage Program, Helena
Danish Environmental Protection Agency (1998) Biological assessment of biological stream quality. Environmental guidelines, 5. Copenhagen. In: Mc Ginnity PM, Mills P, Roche W, Müller M (eds) A desk study to determine a methodology for the monitoring of the ‘morphological conditions’ of Irish Rivers. Final report. Environmental RTDI Programme 2000–2006. Central Fisheries Board—Compass Informatics—EPA
Davenport AJ, Gurnell AM, Armitage PD (2004) Habitat survey and classification of urban rivers. River Res Appl 20(6):687–704
Davies NM, Norris RH, Thoms MC (2000) Prediction and assessment of local stream habitat features using large-scale catchment characteristics. Freshw Biol 45:343–369
Denortier G, Goetghebeur P (1996) Outil d’évaluation de la qualité du milieu physique des cours d’eau. Synthèse, Angers (Agence de l’Eau Rhin-Meuse). In: Mc Ginnity PM, Mills P, Roche W, Müller M (eds) A desk study to determine a methodology for the monitoring of the ‘morphological conditions’ of Irish Rivers. Final report. Environmental RTDI Programme 2000–2006. Central Fisheries Board—Compass Informatics—EPA
Dixon I, Douglas M, Dowe J, Burrows D, Townsend S (2005) A rapid method for assessing the condition of riparian zones in the wet/dry tropics of northern Australia. In: Proceedings of the 4th Australian stream management conference. Department of Primary Industries, Water and Environment, pp 173–178
Dufour S, Piégay H (2009) From the myth of a lost paradise to targeted river restoration: forget natural references and focus on human benefits. River Res Appl 25:568–581
Entwistle N, Heritage G, Milan D (2011) River habitat survey: a useful tool for hydromorphological assessment? Adv River Sci. Swansea UK, Abstracts
Environment Agency (1998) River geomorphology: a practical guide. Environment agency, guidance note 18, National Centre for Risk Analysis and Options Appraisal, London, 56 pp. In: Sear DA, Hill CT, Downes RHE (eds) Geomorphological assessment of riverine SSSIs for the strategic planning of physical restoration. Report NERR013. Natural England Research
Environment Agency (2003) A refined geomorphological and floodplain component. River Habitat Survey FD 1921, GeoRHS fieldwork survey form and guidance manual. Warrington, DEFRA/EA Joint R&D—Project 11793, prepared by University of Newcastle
European Commission (2000) Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 Establishing a Framework for Community Action in the Field of Water Policy. Official Journal L 327, 22/12/2000, Brussels
Feld CK (2004) Identification and measure of hydromorphological degradation in Central European lowland streams. Hydrobiologia 516(1):69–90
Fernández D, Barquin J, Raven PJ (2011) A review of river habitat characterisation methods: indices vs. characterisation protocols. Limnetica 30(2):217–234
Ferreira J, Pádua J, Hughes SJ, Cortes RM, Varandas S, Holmes N, Raven P (2011) Adapting and adopting river habitat survey: problems and solutions for fluvial hydromorphological assessment in Portugal. Limnetica 30(2):263–272
Fitzpatrick FA, Waite JR, D’Arconte PJ, Meador MR, Maupin MA, Gurtz ME (1998) Revised methods for characterizing stream habitat in the national water quality assessment program. US Geological Survey Water Resources Investigations Report 98-4052. Raleigh, North Carolina. In: Mc Ginnity PM, Mills P, Roche W, Müller M (eds) A desk study to determine a methodology for the monitoring of the ‘morphological conditions’ of Irish Rivers. Final report. Environmental RTDI Programme 2000–2006. Central Fisheries Board—Compass Informatics—EPA
Freiland Umeltconsulting (2001b) NÖMORPH. Strukturkartierung ausgewählter Fließgewässer in Niederösterreich. Endbericht - Teil II: Allgemeines und Ergebnisse. (unpublished). In: Mc Ginnity PM, Mills P, Roche W, Müller M (eds) A desk study to determine a methodology for the monitoring of the ‘morphological conditions’ of Irish Rivers. Final report. Environmental RTDI Programme 2000–2006. Central Fisheries Board—Compass Informatics—EPA
Freiland Umweltconsulting (2001a) NÖMORPH. Strukturkartierung ausgewählter Fließgewässer in Niederösterreich. Endbericht - Teil I: Methodik. (unpublished). In: Mc Ginnity PM, Mills P, Roche W, Müller M (eds) A desk study to determine a methodology for the monitoring of the ‘morphological conditions’ of Irish Rivers. Final report. Environmental RTDI Programme 2000–2006. Central Fisheries Board—Compass Informatics—EPA
Frissel CA, Liss WJ, Warren CE, Hurley MD (1986) A hierarchical framework for stream habitat classification: viewing streams in a watershed context. Environ Manag 10(2):199–214
Fryirs KA (2003) Guiding principles for assessing geomorphic river condition: application of a framework in the Bega catchment, South Coast, New South Wales, Australia. Catena 53:17–52
Fryirs K, Brierley GJ (2013) Geomorphic analysis of river systems: an approach to reading the landscape. Wiley, Chichester
Fryirs KA, Arthington A, Grove J (2008) Principles of river condition assessment. In: Brierley G, Fryirs KA (eds) River futures. An integrative scientific approach to river repair. Society for Ecological Restoration International, Island Press, Washington, pp 100–124

Galli J (1996) Rapid stream assessment technique (RSAT) field methods. Metropolitan Washington Council of Governments, Washington, D.C. In: Clean Water Services, Watershed Management Division (Oregon) (2000) Tualatin River Basin Rapid Stream Assessment Technique (RSAT)—Watersheds 2000 Field Methods, Montgomery County Department of Environmental Protection; Department of Environmental Programs—Metropolitan Washington Council of Governments

González Del Tánago M, García De Jalón D (2011) Riparian quality index (RQI): a methodology for characterizing and assessing environmental conditions of riparian zones. Limnetica 30(2):235–254

Hallde'n A, Liliegren Y, Lagerkvist G (2002) Biotopkartering - Vattendrag. Metodik för kartering av biotoper i ochi anslutning till vattendrag. ISSN: 1101-9425. Meddelande nr 2002:55. (In Swedish). Jönköping: Länsstyrelsen i Jönköpings län. In: Molin J, Kagervall AJ (eds) Linking habitat characteristics with juvenile density to quantify Salmo salar and Salmo trutta smolt production in the river Savaran, Sweden. Fish Manag Ecol 17:446–453

Halwas KL, Church M (2002) Channel units in small, high gradient streams on Vancouver Island, British Columbia. Geomorphology 43:243–256

Harding JS, Clapcott JE, Quinn JM, Hayes JW, Joy MK, Storey RG, Greig J, Hay HS, James T, Beech MA, Ozane R, Meredith AS, Boothroyd IKG (2009) Stream habitat assessment protocols for wadeable rivers and streams of New Zealand, University of Canterbury

Harrelson CC, Rawlins CL, Potyondy JP (1994) Stream channel reference sites: an illustrated guide to field technique. General Technical Report RM-245. USDA

Healey M, Raine A, Parsons L, Cook N (2012) River condition index in New South Wales: method development and application. NSW Office of Water, Sydney

Henriksen JA, Heasley J, Kennen JG, Niewsand S (2006) Users' manual for the hydroecological integrity assessment process. US Geological Survey, Biological Resources Discipline, Open File Report 2006-1093

Idaho Department of Environmental Quality (2004) Beneficial use reconnaissance program field manual for streams (BURP). Beneficial Use Reconnaissance Program Technical Advisory Committee, Idaho Department of Environmental Quality, Boise

Ilnicki P, Lewandowski P (1997) Ekomorfologiczna waloryza-cja dróg wodnych Wielkopolski. Bogucki Wyd. Nauk., Po-znań. In: Grzybowski M, Endler Z (eds) Ecomorphological evaluation of the Łyna river along the Kotovo-Ardapy section. Quaest Geogr 31(1):51–65

Ilnicki P, Gołdyn R, Soszka H, Górecki K, Grzybowski M, Krzemińska A, Lewandowski P, Skocki K, Sojka M, Marcinkiewicz M (2009) Opracowanie metodyk monitoringu i klasyfikacji hydromorfologicznych elementów jakości jednolitych części wód rzecznych i jeziornych, zgodnie z wymogami Ramowej Dyrektywy Wodnej. ETAP I–II. Zadanie 1, 2 i 3. Kod CPV: 9071 1500–9. Nomenklatura wg CPV: 90711500–9. Poznań listopad 2009 roku GEPOL sp. z o.o., Poznań. In: Ilnicki P, Górecki K, Grzybowski M, Krzemińska A, Lewandowski P, Sojka M (eds) Principles of hydromorphological surveys of Polish rivers. J Water Land Dev 14:3–13

Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA) (2011) Implementazione della Direttiva 2000/60/CE. Analisi e valutazione degli aspetti idromorfologici. Versione 1.1. ISPRA, Roma

Jansen A, Robertson A, Thompson L, Wilson A (2005) Rapid appraisal of riparian condition. Version two. River and Riparian Land Management, Technical Guideline 4A. Canberra, Land & Water Australia

Kaarup P (1999) Indeks for fysisk variation i vandløb. Vand og Jord nr. 6. In: Mc Ginnity PM, Mills P, Roche W, Müller M (eds) A desk study to determine a methodology for the monitoring of the 'morphological conditions' of Irish Rivers. Final report. Environmental RTDI Programme 2000–2006. Central Fisheries Board—Compass Informatics—EPA

Kansas Department of Wildlife and Parks (2004) Subjective evaluation of aquatic habitats. Kansas Department of Wildlife and Parks, Environmental Services Section, Topeka

Kaufmann PR, Levine P, Robison EG, Seeliger C, Peck DV (1999) Quantifying physical habitat in wadeable streams. EPA/620/R-99/003. US Environmental Protection Agency, Washington D.C

King JM, Tharme RE, de Villiers MS (eds) (2008) Environmental flow assessments for rivers: manual for the building block methodology. WRC Report No TT 354/08. Updated Edition. Water Research Commission, Pretoria

Kleynhans CJ, Louw MD, Thirion C, Rossouw NJ, Rowntree KM (2005) River EcoClassification: manual for EcoStatus determination (version 1). Joint Water Research Commission and Department of Water Affairs and Forestry, South Africa. Report No. KV 168/05

Kleynhans CJ, Mackenzie J, Louw MD (2007) Module F: Riparian Vegetation Response Assessment Index in River EcoClassification: manual for EcoStatus determination (version 2). Joint Water Research Commission and Department of Water Affairs and Forestry report. WRC Report No. KV 168/05

Kleynhans CJ, Louw MD, Graham M (2008) Module G: EcoClassification and EcoStatus determination in River EcoClassification: index of habitat integrity (Section 1, Technical manual). Joint Water Research Commission and Department of Water Affairs and Forestry report. WRC Report No. TT 377-08

Kondolf GM, Montgomery D, Piégay H, Schmitt L (2003) Geomorphic classifications of rivers and streams. In: Kondolf GM, Piégay H (eds) Tools in fluvial geomorphology, chapter 7. Wiley, Chichester

Ladson AR, White LJ, Doolan JA, Finlayson BL, Hart BT, Lake PS, Tilleard JW (1999) Development and testing of an index of stream condition for waterway management in Australia. Freshw Biol 41:453–468

Langhammer J (2007) HEM Hydroekologický monitoring. Metodika pro monitoring hydromorfologických ukazatelů ekologické kvality vodních toků. PřF UK, Praha, 47 pp. In: Langhammer J (ed) Applicability of hydromorphological monitoring data to locate flood risk reduction measures: Blanice River basin, Czech Republic. Environ Monit Assess 152(1):379–392

LAWA (2000) Gewässerstrukturgütebewertung in der Bundesrepublik Deutschland. Verfahren für kleine und mittelgroße Fließgewässer, Schwerin, Länderarbeitsgemeinschaft Wasser. In: Kamp U, Binder W, Holzl K (eds) River habitat monitoring and assessment in Germany. Environ Monit Assess 127(1–3): 209–226

LAWA (2002a) Gewässerstrukturkartierung in der Bundesrepublik Deutschland. Verfahren für mittelgroße bis große Fließgewässer. Länderarbeitsgemeinschaft Wasser, Schwerin

LAWA (2002b) Gewässerstrukturgütekartierung in der Bundesrepublik Deutschland - Übersichtsverfahren. Empfehlungen Oberirdische Gewässer. Entwurf April 2002. Länderarbeitsgemeinschaft Wasser

Lazorchak JM, Herlihy AT, Green J (1998) Rapid habitat and visual stream assessments. Section 14. In: US Environmental Protection Agency (2004) WSAss—wadeable streams assessment: field operations manual. Vol. EPA841-B-04-004

Lehotský M, Grešková A (2007) Fluvial geomorphological approach to river assessment—methodology and procedure. Geograficky Casopis 59(2):107–129

Liechti P, Sieber U, Bundi U, Frutiger A, Hütte M, Peter A, von Blücher U, Willi AP, Göldi C, Kupper U, Meier W, Niederhauser P (1998) Méthodes d'analyse et d'appréciation des cours d'eau en Suisse - Système modulaire gradué, Institut fédéral pour l'aménagement, l'épuration et la protection des eaux (IFAEPE); Office fédéral de l'économie des eaux (OFEE); Amt für Abfall, Wasser, Energie und Luft (AWEL), canton de Zurich

Magdaleno F, Martínez R, Roch V (2010) Índice RFV para la valoración del estado del bosque de ribera. Ingeniería Civil 157:85–96

Maine Department of Environmental Protection (2009) Stream survey manual. Volume I and II (and Appendices). Maine Stream Team Program of the Maine Department of Environmental Protection

Martínez Santa-María C, Fernández Yuste JA (2010) IAHRIS 2.2. Indicators of hydrologic alteration in rivers. User's manual. Ministry of the Environment, Polytechnic University of Madrid, CEDEX. http://www.ecogesfor.org/IAHRIS_es.html

Matoušková M (2006) Dílčí zpráva z grantu GAČR 205/05/P102. Faculty of Science, Charles University in Prague. In: Weiss A, Matouskova M, Matschullat J (eds) Hydromorphological assessment within the EU-Water Framework Directive—trans-boundary cooperation and application to different water basins. Hydrobiologia 603:53–72

Mc Ginnity PM, Mills P, Roche W, Müller M (2005) A desk study to determine a methodology for the monitoring of the 'morphological conditions' of Irish Rivers. Final report. Environmental RTDI Programme 2000–2006. Central Fisheries Board—Compass Informatics—EPA

Meile T, Boillat IL, Schleiss AJ (2011) Hydropeaking indicators for characterization of the Upper-Rhone River in Switzerland. Aquat Sci 73:171–182

Ministry of the Environment (1999) Revised Stormwater Management Guidelines Draft Report. Ontario Ministry of the Environment. In: Central Lake Ontario Conservation (2011) Black/Harmony/Farewell Creek Watershed. Existing conditions report. Chapter 13—Fluvial Geomorphology. Durham Region

Minnesota Pollution Control Agency (2002) Physical habitat and water chemistry assessment protocol for wadeable stream monitoring sites. Minnesota Pollution Control Agency, St. Paul

Muhar S, Jungwirth M (1998) Habitat intgegrity of running waters—assessment criteria and their biological relevance. Hydrobiologia 386:195–202. In: Mc Ginnity PM, Mills P, Roche W, Müller M (eds) A desk study to determine a methodology for the monitoring of the 'morphological conditions' of Irish Rivers. Final Report. Environmental RTDI Programme 2000–2006. Central Fisheries Board—Compass Informatics—EPA

Mühlmann H (2010) Leitfaden zur zustandserhebung in fliessgewässern - Hydromorphologie. Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft (Wien). http://wisa.lebensministerium.at/article/articleview/81530/1/29401/

Munné A, Prat N (1998) QBR: Un índice rápido para la evaluación de la calidad de los ecosistemas de ribera. Tecnología del Agua 175:20–37

Munné A, Prat N, Sola C, Bonada N, Rieradevell M (2003) A simple field method for assessing the ecological quality of riparian habitat in rivers and streams: QBR index. Aquat Conserv Mar Freshw Ecosyst 13:147–163

Munné A, Solà C, Pagés J (2006) HIDRI: Protocolo para la valoración de la calidad hidromorfológica de los ríos. Agència Catalana de l'Aigua, Barcelona

Murphy M, Toland M (2012) River hydromorphology assessment technique (RHAT). Training guide. Northern Ireland Environment Agency, Department of the Environment, Version 2012

National Environmental Research Institute (1999) National physical habitat index. In: Mc Ginnity PM, Mills P, Roche W, Müller M (eds) A desk study to determine a methodology for the monitoring of the 'morphological conditions' of Irish Rivers. Final report. Environmental RTDI Programme 2000–2006. Central Fisheries Board—Compass Informatics—EPA

Newson MD, Large ARG (2006) 'Natural' rivers, 'hydromorphological quality' and river restoration: a challenging new agenda for applied fluvial geomorphology. Earth Surf Process Landf 31:1606–1624

Ohio Environmental Protection Agency (2002) Field evaluation manual for Ohio's primary headwater habitat streams. Final Version 1.0. Division of Surface Water, Ohio Environmental Protection Agency, Columbus, Ohio. In: Kasich J, Taylor M, Nally S (eds) Field evaluation manual for Ohio's primary headwater habitat streams, Version 3.0. Ohio

Oliveira SV, Cortes RMV (2005) A biologically relevant habitat condition index for streams in northern Portugal. Aquat Conserv Mar Freshw Ecosyst 15(2):189–210

Ollero A, Ballarín D, Díaz E, Mora D, Sánchez M, Acín V, Echeverría MT, Granado D, Ibisate A, Sánchez L, Sánchez N (2007) Un indice hidrogeomorfologico (IHG) para la evaluacion del estado ecologico de sistemas fluviales. Geographicalia 52:113–141

ONEMA (2010) Des étapes et des outils… Les outils de connaissance de l'hydromorphologie des cours d'eau français. Restauration physique des cours d'eau - Connaissance

Oregon Watershed Enhancement Board (2000) Oregon watershed assessment manual. http://www.oregon.gov/OWEB/pages/docs/pubs/or_wsassess_manuals.aspx

Overton CK, Wollrab SP, Roberts CB, Radko MA (1997) Fish and fish habitat standard inventory procedures handbook. United States Department of Agriculture, Forest Service

Paetzold A, Yoshimura C, Tockner K (2008) Riparian arthropod responses to flow regulation and river channelization. J Appl Ecol 45:894–903

Pardo I, Álvarez M, Casas J, Moreno JL, Vivas S, Bonada N, Alba-Tercedor J, Jáimez-Cuéllar P, Moyà G, Prat N, Robles S, Suárez ML, Toro M, Vidal-Abarca MR (2002) El hábitat de los ríos mediterráneos. Diseño de un índice de diversidad de hábitat. Limnetica 21(3–4):115–133

Parsons M, Thoms MC, Norris RH (2004) Development of a standardised approach to river habitat assessment in Australia. Environ Monit Assess 98:109–130. In: Mc Ginnity PM, Mills P, Roche W, Müller M (eds) A desk study to determine a methodology for the monitoring of the 'morphological conditions' of Irish Rivers. Final report. Environmental RTDI Programme 2000–2006. Central Fisheries Board—Compass Informatics—EPA

Pedersen ML, Baattrup-Pedersen A (2003) Økologisk overvågning i vandløb og på vandløbsnære arealer under NOVANA 2004-2009. Danmarks Miljøundersøgelser. Teknisk Anvisning fra DMU nr. 21. In: National Environmental Research Institute and Slovak Hydrometeorological Institute (2004) Establishment of the Protocol on Monitoring and Assessment of the Hydromorphological Elements (Slovakia). Final report

Person E, Peter A (2012) Influence of hydropeaking on brown trout habitat. In: Conference paper 9th international symposium on Ecohydraulics

Petersen RC (1992) The RCE: a Riparian, Channel, and Environmental Inventory for small streams in the agricultural landscape. Freshw Biol 27(2):295–306. doi:10.1111/j.1365-2427.1992.tb00541.x

Plafkin JL, Barbour MT, Porter KD, Gross SK, Hughes RM (1989) Rapid bioassessment protocols for use in streams and rivers-Benthic macroinvertebrates and fish. USEPA/440/4-89-001. US Environmental Protection Agency. Washington, D.C. In: Barbour MT, Gerritsen J, Snyder BD, Stribling JB (eds) Rapid bioassessment protocols for use in streams and wadeable rivers:

periphyton, benthic macroinvertebrates, and fish, 2nd edn. EPA 841-B-99-002 U.S

Platts WS, Megahan WF, Minshall GW (1983) Methods for evaluating stream, riparian, and biotic conditions. US Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. Ogden, UT

Poff NL, Zimmerman JKH (2010) Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flow. Freshw Biol 55:147–170

Poff NL, Allan JD, Palmer MA, Hart DD, Richter BD, Arthington AH, Rogers KH, Meyer JL, Stanford JA (2003) River flows and water wars: emerging science for environmental decision making. Front Ecol Environ 1:298–306

Prichard D, Barrett H, Cagney J, Clark R, Fogg J, Gebhardt K, Hansen PL, Mitchell B, Tippy D (1998) Riparian area management: process for assessing proper functioning condition. Technical Reference 1737-9, BLM/SC/ST-9/003+1737+REV95+REV98. Bureau of Land Management, Denver

Rankin ET (1989) The qualitative habitat evaluation index (QHEI): rationale, methods, and application. Div. Water Qual. Plan. & Assess., Ecol. Assess. Sect., Columbus, Ohio. In: Taft B, Koncelik JP (eds) Methods for assessing habitat in flowing waters: using the qualitative habitat evaluation index (QHEI). Ohio EPA

Raven PJ, Fox P, Everard M, Holmes NTH, Dawson FH (1997) River habitat survey: A new system for classifying rivers according to their habitat quality. Freshwater Quality: Defining the Indefinable? In: Raven PJ, Holmes NTH, Charrier P, Dawson FH, Naura M, Boon PJ (eds) Towards a harmonized approach for hydromorphological assessment of rivers in Europe: a qualitative comparison of three survey methods. Aquat Conserv Mar Freshw Ecosyst 12(4):405–424

Raven PJ, Holmes NTH, Charrier P, Dawson FH, Naura M, Boon PJ (2002) Towards a harmonized approach for hydromorphological assessment of rivers in Europe: a qualitative comparison of three survey methods. Aquat Conserv Mar Freshw Ecosyst 12(4):405–424

Raven P, Holmes N, Pádua J, Ferreira J, Hughes S, Baker L, Taylor L, Seager K (2009) River habitat survey in Southern Portugal. Results from 2009. Environment Agency, Bristol

Richter BD, Baumgartner JV, Powell J, Braun DP (1996) A method for assessing hydrologic alteration within ecosystems. Conserv Biol 10(4):1163–1174

Rinaldi M, Surian N, Comiti F, Bussettini M (2013a) A method for the assessment and analysis of the hydromorphological condition of Italian streams: the morphological quality index (MQI). Geomorphology 180–181:96–108. doi:10.1016/j.geomorph.2012.09.009

Rinaldi M, Belletti B, Van de Bund W, Bertoldi W, Gurnell A, Buijse T, Mosselman E (2013b) Review on eco-hydromorphological methods. Deliverable 1.1, REFORM (REstoring rivers FOR effective catchment Management), Project funded by the European Commission within the 7th Framework Programme (2007–2013), Topic ENV.2011.2.1.2-1 hydromorphology and ecological objectives of WFD, Grant Agreement 282656

Rinaldi M, Wyzga B, Dufour S, Bertoldi W, Gurmenll AM (2013c) River processes and implications for fluvial ecogeomorphology: a European perspective. In: Schroder JF (ed) Treatise in geomorphology 12(4):37–52

Rosgen DL (1996) Applied river morphology. Wildland Hydrology, Pagosa Springs, CO. In: Rosgen D (ed) The natural channel design method for river restoration. Wildland Hydrology

Rosgen DL (2006) A watershed assessment for river stability and sediment supply (WARSSS). Wildland Hydrology Books, Fort Collins. http://www.epa.gov/warsss/

Rowntree KM, Wadeson RA (2000) Field manual for channel classification and condition assessment Institute for Water Quality Studies. Department of Water Affairs and Forestry, Pretoria

Saint-Jaques N, Richard Y (1998) Développement d'un indice de qualité de la bande riveraine : application à la rivière Chaudière et mise en relation avec l'intégrité biotique du milieu aquatique. In: Le bassin de la rivière Chaudière: qualité de la bande riveraine. Direction des écosystèmes aquatiques - Ministère de l'Environnement et de la faune (Quebec), 6.1–6.41

Scheifhacken N, Haase U, Gram-Radu L, Kozovyi R, Berendonk TU (2012) How to assess hydromorphology? A comparison of Ukrainian and German approaches. Environ Earth Sci 65:1483–1499. doi:10.1007/s12665-011-1218-2

Schneiders A, Verhaert E, Blust GD, Wils C, Nervoets L, Verheyen R (1993) Towards an ecological assessment of watercourses. J Aquat Ecosyst Health 2:29–38. In: Mc Ginnity PM, Mills P, Roche W, Müller M (eds) A desk study to determine a methodology for the monitoring of the 'morphological conditions' of Irish Rivers. Final report. Environmental RTDI Programme 2000–2006. Central Fisheries Board—Compass Informatics—EPA

Schumm SA, Harvey MD, Watson CC (1984) Incised channels: morphology, dynamics and control. Water Resources Publications, Littleton, Colorado. In: Darby SE, Simon A (eds) (1999) Incised river channels: processes, forms, engineering and management. Wiley, New York 2:19–33

Sear DA, Hill CT, Downes RHE (2008) Geomorphological assessment of riverine SSSIs for the strategic planning of physical restoration. Report NERR013. Natural England Research

Shiau J-T, Wu F-C (2008) A histogram matching approach for assessment of flow regime alteration: application to environmental flow optimization. River Res Appl 24(7):914–928

Siligardi M, Bernabei S, Cappeletti C, Chierici E, Ciutti F, Egaddi F, Franceschini A, Maiolini B, Mancini L, Minciardi MR, Monauni C, Rossi GL, Sansoni G, Spaggiari R, Zanetti M (2002) I.F.F. Indice di funzionalità fluviale. Manuale ANPA

Simon A, Downs PW (1995) An interdisciplinary approach to evaluation of potential instability in alluvial channels. Geomorphology 12(3):215–232. In: Heeren DM, Mittelstet AR, Fox GA, Storm DE, Al-Madhhachi AT, Midgley TL, Stringer AF, Stunkel KB, Tejral RD (eds) Using rapid geomorphic assessments to assess streambank stability in Oklahoma Ozark streams. Am Soc Agric Biol Eng 55(3):957–968

Simon A, Hupp CR (1986) Channel evolution in modified tennessee channels. Proceedings of the fourth interagency sedimentation conference, Las Vegas, Nevada. In: Darby SE, Simon A (eds) (eds) Incised river channels: processes, forms, engineering and management. Wiley, New York 1:3–18

Skriver J, Riis T, Carl J, Baattrup-Pedresen A, Friberg N, Ernst ME, Frandsen SB, Sode A, Wiberg-Larsen P (1999) Biologisk vandløbskvalitet (DVFI). Udvidet biologisk program. NOVA 2003. Afdeling for Vandløbsøkologi og Afdeling for Sø- og Fjordøkologi. In: Mc Ginnity PM, Mills P, Roche W, Müller M (eds) A desk study to determine a methodology for the monitoring of the 'morphological conditions' of Irish Rivers. Final report. Environmental RTDI Programme 2000–2006. Central Fisheries Board—Compass Informatics—EPA

Smith D, Ammann A, Bartoldus C, Brinson MM (1995) An approach for assessing wetland functions using hydrogeomorphic classification, reference wetlands, and functional indices. Vol Wetlands Research Program Technical Report WRP-DE-9. US Army Corps of Engineers Waterways Experiment Station

Spiegler A, Godina G, Imhoff K, Nachtnebel O, Pelikan S (1989) Strukturökologische Methode zur Bestandsaufnahme und Bewertung von Fließgewässern. Planungen und Untersuchungen. Bundesministerium für Land- und Forstwirtschaft, Wasserwirtschaftskataster. Wien. In: Mc Ginnity PM, Mills P, Roche W, Müller M (eds) A desk study to determine a methodology for the monitoring of the 'morphological conditions' of Irish Rivers. Final report. Environmental RTDI Programme 2000–2006. Central Fisheries Board—Compass Informatics—EPA

Starr RR (2009) Stream Assessment Protocol. Anne Arundel County, Maryland—US Fish & Wildlife Service

Starr RR, Mc Candless T (2001) Stream and riparian habitats rapid assessment protocol. Chesapeake Bay Field Office, US Fish and Wildlife Service, Annapolis. In: Somerville DE, Pruitt BA (eds) Physical stream assessment: a review of selected protocols for use in the Clean Water Act Section 404 Program. vol 3 W-0503-NATX. US Environmental Protection Agency, Office of Wetlands, Oceans, and Watersheds, Wetlands Division

Stranko S, Boward D, Kilian J, Becker A, Ashton M, Schenk A, Gauza R, Roseberry-Lincoln A, Kazyak P (2010) Maryland biological stream survey, round three field sampling manual. Revised version. Maryland Department of Natural Resources

Tavzes B, Urbanic G (2009) New indices for assessment of hydromorphological alteration of rivers and their evaluation with benthic invertebrate communities; Alpine case study. Rev Hydrobiol 2:133–161

The Nature Conservancy (2009) Indicators of hydrologic alteration version 7.1. User's manual

Thorne CR (1998) Geomorphological stream reconnaissance handbook. Wiley, Chichester

Tickner D, Armitage PD, Bickerton MA, Hall KA (2000) Assessing stream quality using information on mesohabitat distribution and character. Aquat Conserv Mar Freshw Ecosyst 10(3):179–196

Tockner K, Ward JV (1999) Biodiversity along riparian corridors. Large Rivers 11(3). Arch Hydrobiol Suppl 115(3):293–310

UK Technical Advisory Group on the WFD (2008) UK environmental standards and conditions (phase 1)—final. Vol. SR1-2006

US Department of Agriculture (2009) Stream Visual assessment protocol version 2, vol. Subpart B—conservation planning. USDA Natural Resources Conservation Service

US Environmental Protection Agency (1997) Volunteer stream monitoring: a methods manual. In: Mc Ginnity PM, Mills P, Roche W, Müller M (eds) A desk study to determine a methodology for the monitoring of the 'morphological conditions' of Irish Rivers. Final report. Environmental RTDI Programme 2000–2006. Central Fisheries Board—Compass Informatics—EPA

US Environmental Protection Agency (2004) Wadeable streams assessment (WASss): field operations manual. EPA841-B-04-004. Office of Water and Office of Research and Development, Washington, DC

US Forest Service (2006) Stream inventory handbook—level I and II. Vol. 2.6. US Forest Service, Pacific Northwest Region

Valette L, Chandesris A, Malavoi JR, Suchon Y, Willet B (2010) Protocole AURAH-CE AUdit RApide de l'Hydromorphologie des Cours d'Eau. Méthode de recueil d'informations complémentaires à SYRAH-CE sur le terrain, Pôle hydroécologie des cours d'eau - Onema/Cemagref

van Dam O, Osté AJ, de Groot B, van Dorst MAM (2007) Handboek Hydromorfologie. Monitoring en afleiding hydromorfologische parameters Kaderrichtlijn Water. Directoraat-generaal Rijkswaterstaat, Waterdienst/Data- en ICT-Dienst, Lelystad/Delft. ISBN 9789036914512

Vaughan IP, Diamond M, Gurnell AM, Hall KA, Jenkins A, Milner NJ, Naylor LA, Sear DA, Woodward G, Ormerod SJ (2009) Integrating ecology with hydromorphology: a priority for river science and management. Aquat Conserv Mar Freshw Ecosyst 19:113–125

Vermont Agency of Natural Resources (2010) Vermont stream geomorphic assessment. Appendix A—field forms. Waterbury http://www.vtwaterquality.org/rivers/htm/rv_geoassesspro.htm

Ward TA, Tate KW, Atwill ER (2003) Visual assessment of Riparian health. Vol. ANR Publication 8089, Rangeland Monitoring Series. University of California

Weiss A, Matouskova M, Matschullat J (2008) Hydromorphological assessment within the EU-Water Framework Directive—transboundary cooperation and application to different water basins. Hydrobiologia 603:53–72

Werth W (1987) Ökomorphologische Gewässerbewertung in Oberösterreich (Gewässerzustandkartierungen). Eco-morphological classification of channels in Upper Austria. In: Oesterreichische Wasserwirtschaft 39 (5/6). Wien (Springer): 121–128. In: Mc Ginnity PM, Mills P, Roche W, Müller M (eds) A desk study to determine a methodology for the monitoring of the 'morphological conditions' of Irish Rivers. Final report. Environmental RTDI Programme 2000–2006. Central Fisheries Board—Compass Informatics—EPA

Wilhelm J, Allan J, Wessell K, Merritt R, Cummins K (2005) Habitat assessment of non-wadeable rivers in Michigan. Environ Manag 36:592–609. doi:10.1007/s00267-004-0141-7

Wils C, Schneiders A, Bervoets L, Nagels A, Weiss L, Verheyen RF (1994) Assessment of the ecological value of rivers in Flanders (Belgium). Water Sci Technol 30(10): 37–47. In: Goethals P, De Pauw N (eds) Development of a concept for integrated ecological river assessment in Flanders, Belgium. J Limnol 60(1):7–16

Winward AF (2000) Monitoring the vegetation resources in Riparian areas. General Technical Report RMRS-GTR-47. US Department of Agriculture

Wyżga B, Amirowicz A, Radecki-Pawlik A, Zawiejska J (2009) Hydromorphological conditions, potential fish habitats and the fish community in a mountain river subjected to variable human impacts, the Czarny Dunajec, Polish Carpathians. River Res Applic 25(5):517–536

Xia T, Zhu W, Xin P, Li L (2010) Assessment of urban stream morphology: an integrated index and modelling system. Environ Monit Assess 167(1–4):447–460

Yetman KT (2001) Stream corridor assessment survey. Survey protocols. Watershed Restoration Division Chesapeake and Coastal Watershed Services Maryland Maryland Department of Natural Resources

Zolezzi G, Bellin A, Bruno MC, Maiolini B, Siviglia A (2009) Assessing hydrological alterations at multiple temporal scales: Adige River, Italy. Water Resour Res 45(12):W12421. doi:10.1029/2008WR007266