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Characterising physical habitats and fluvial hydromorphology: A new system for the survey and classification of river geomorphic units

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ABSTRACT

Geomorphic units are the elementary spatial physical features of the river mosaic at the reach scale that are nested within the overall hydromorphological structure of a river and its catchment. Geomorphic units also constitute the template of physical habitats for the biota. The assessment of river hydromorphological conditions is required by the European Water Framework Directive 2000/60 (WFD) for the classification and monitoring of water bodies and is useful for establishing links between their physical and biological conditions. The spatial scale of geomorphic units, incorporating their component elements and hydraulic patches, is the most appropriate to assess these links. Given the weakness of existing methods for the characterisation and assessment of geomorphic units and physical habitats (e.g., lack of a well-defined spatiotemporal framework, terminology issues, etc.), a new system for the survey and characterisation of river geomorphic units is needed that fits within a geomorphologically meaningful framework.

This paper presents a system for the survey and classification of geomorphic units (*GUS*, geomorphic units survey and classification system) aimed at characterising physical habitats and stream morphology. The method is embedded into a multiscale, hierarchical framework for the analysis of river hydromorphological conditions. Three scales of geomorphic units are considered (i.e., macro-units, units, sub-units), organised within two spatial domains (i.e., bankfull channel and floodplain). Different levels of characterisation can be applied, depending on the aims of the survey: broad, basic, and detailed level. At each level, different, complementary information is collected. The method is applied by combining remote sensing analysis and field survey, according to the spatial scale and the level of description required. The method is applicable to most of fluvial conditions, and has been designed to be flexible and adaptable according to the objectives (e.g., reach characterisation, assessment, monitoring) and available data (e.g., image resolution). The method supports integrated hydromorphological assessment at the reach scale (e.g., the Morphological Quality Index, *MQI*) and therefore contributes to better establishing links between hydromorphological conditions at the reach scale, characteristic geomorphic units, and related biological conditions.

1. Introduction

Rivers are complex systems where abiotic and biotic components interact at different spatial and temporal scales. Rivers can thus be viewed as a set of hierarchically organised subsystems, where the smaller spatial and temporal levels nest within those at larger spatial and temporal scales (see for e.g., Frissell et al., 1986; Amoros and Petts, 1993; Brierley and Fryirs, 2005; Rinaldi et al., 2013; Gurnell et al., 2016a; Figure 1). Within this nested hierarchical system, processes and forms at larger scales dominate and determine processes and forms at smaller scales (e.g., Brierley et al., 2013; Gurnell et al., 2016a).

Within the nested hierarchical framework, geomorphic units represent pieces of the mosaic that characterise river morphology at the reach scale (building blocks; sensu Fryirs and Brierley, 2013), whereby a reach is 'a section of river along which boundary conditions are sufficiently uniform that the river maintains a near consistent internal set of

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process-form interactions' (Gurnell et al., 2016a). Geomorphic units are thus the physical manifestation of the processes of water flow and sediment transport that are influenced by factors acting at the reach (e.g., slope, substrate, vegetation, valley setting) and larger scales. Indeed, reaches of the same morphological type (e.g., wandering, sinuous), usually exhibit similar assemblages of geomorphic units. A geomorphic unit corresponds to an area containing a landform created by the erosion or deposition of sediment, or by bedrock. River geomorphic units are located within the river channel (e.g., riffles, pools, bars, etc.) or on the floodplain (e.g., terraces, oxbow lakes, etc.) and typically occupy an area extending from 0.1 to 20 times the channel width (Gurnell et al., 2016a). They can be either entirely sedimentary units, or they can also incorporate living or dead vegetation (e.g., large wood).

Because river hydromorphology has been incorporated into the European Water Framework Directive 2000/60 (WFD), river physical forms and processes have been increasingly highlighted as essential components in the analysis and management of river systems. In particular, river hydromorphology may allow a realistic representation of physical structures and dynamics to be integrated into biological and ecological theories (Poole, 2010), which is useful for establishing links between river physical and biological conditions. In this context, the spatial scale of geomorphic units, incorporating their component elements and hydraulic patches (Fig. 1), is the most appropriate to assess these links. Indeed, these spatial units (e.g., riffles, pools, bars, islands, etc., but also individual boulders, sediment patches, plants or wood pieces, etc.) constitute distinct habitats for fluvial (aquatic and riparian) fauna and flora, including temporary habitats such as refugia from disturbance or predation, spawning, etc. These provide the physical template that underpins the delivery of the key environmental conditions required to support the river's biota (Wyrick et al., 2014).

Several terms have been used in the literature to identify discernible physical units of river channel morphology including: river landform; morphological unit; hydromorphological unit; physical/hydraulic biotope; ecotope (e.g., Padmore, 1998; Van der Molen et al., 2003; Milan et al., 2010; Vezza et al., 2014; Wyrick et al., 2014; Wheaton et al., 2015). Although the precise definitions of these terms may differ to some degree, all refer to features that could be viewed as river geomorphic units in the context of this paper.

Several methods, protocols, procedures, and frameworks have been developed for the survey, characterisation, and classification of physical habitats in river channels and their margins since the 1980s. Some of them can be described as river habitat surveys or physical habitat assessments, often leading to the assessment of indices of river habitat quality or degradation (e.g., Platts et al., 1983; Plafkin et al., 1989; Raven et al., 1997; Ladson et al., 1999; National Environmental Research Institute, 1999). These methods provide a framework within which habitat units can be efficiently inventoried and sampled so that the range of physical habitats, their heterogeneity, and the contemporary physical structure of river ecosystems can be characterised. Although these provide very useful information concerning the character of the river at the time of survey, they also have a series of limitations (Belletti et al., 2015a). For example, they view sections of river in rather static isolation without reference to their spatial context or the fact that they may be changing through time, factors that can be incorporated if a spatiotemporal framework is adopted (e.g., Montgomery and Buffington, 1998; Benda et al., 2004; Brierley et al., 2013; Fryirs and Brierley, 2013; Gurnell et al., 2016a). Additionally, the terminology these procedures use to characterise channel forms and geomorphic units often does not encompass the full range recognised within contemporary fluvial geomorphology. For example, often little consideration is given to the wide variety of bed morphologies found in steep, mountain, cobble- or boulder-bed streams, such as those considered by Halwas and Church (2002), Wohl (2010), and Comiti and Mao (2012), for example. In the same way, the variety of geomorphic units

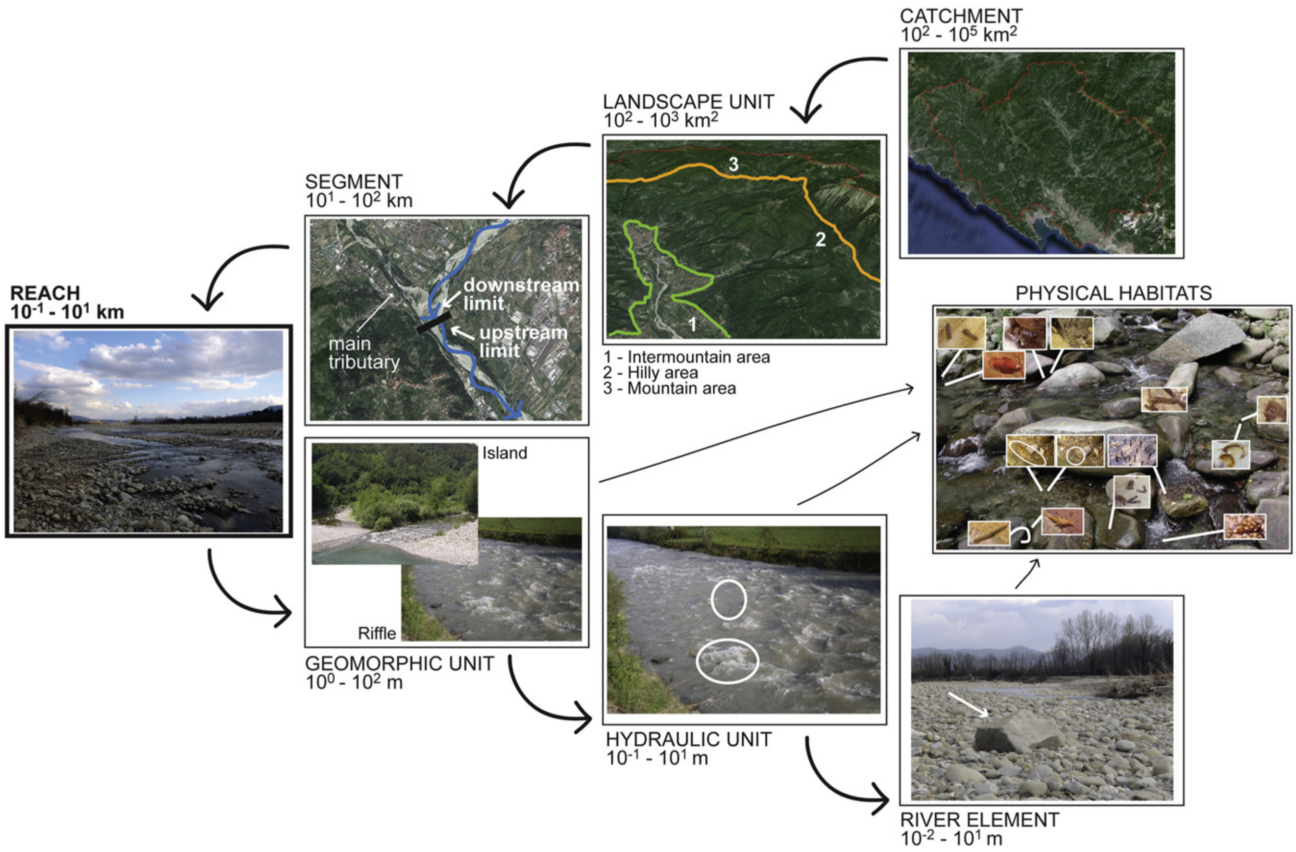


Fig. 1. Relation between spatial units and physical habitats within the nested hierarchical framework. (Source: modified from Mosselman et al., 2015; physical habitats picture by G. Sansoni).

found in rivers with complex, transitional, or multithread patterns (i.e., wandering or braided) is often poorly incorporated. In the case of large rivers (e.g., many piedmont Alpine rivers), most of the existing field-based procedures do not fully integrate remote sensing techniques capable of recognising the variability and complexity of features on these large systems. Many of these methods also fail to recognise that the natural geomorphic structure of some river types may be very simple (e.g., bedrock mountain rivers) but rather identify high spatial geomorphic heterogeneity with pristine or lightly modified river conditions, as has been highlighted, for example, by Fryirs (2003) and Barquín et al. (2011).

Other procedures developed since the early 1990s to map, characterise, or classify river physical habitats include those described by Hawkins et al. (1993), Jowett (1993), Wadeson (1995), Maddock and Bird (1996), Padmore et al. (1996), and more recently Thomson et al. (2001), Clifford et al. (2006), Harvey and Clifford (2009), and Zavadil et al. (2012). These procedures generally do not include a quality assessment based on one or more synthetic indices. They also focus entirely on aquatic habitats, in response to the interest of scientists and river managers in aquatic organisms. Many are based on the identification and classification of *flow types* such as free fall, broken standing waves, etc. (e.g., Padmore, 1998; Newson and Newson, 2000; Zavadil and Stewardson, 2013), which are also incorporated in some of the methods described above. These are used to indicate the template of physical habitats at the microhabitat scale. However, notably such flow types are highly temporally variable, depending strongly on discharge conditions at the moment of observation (Zavadil and Stewardson, 2013) and on local, frequent morphological changes.

In addition to field surveys and field-based assessments, other methodological advances have allowed information on geomorphic units and physical habitats to be extracted in many new ways.

First, numerous automated or semiautomated procedures have been developed for the extraction of spatial fluvial features including but not confined to geomorphic units (e.g., Milan et al., 2010; Belletti et al., 2013, 2014; Wyrick et al., 2014; Demarchi et al., 2016).

Second, the development of habitat simulation models, which quantify the spatial variability of hydraulic parameters (e.g., flow velocity, water depth, etc.) for different flow discharges have contributed a temporal as well as spatial perspective on physical habitat (e.g., PHABSIM, Bovee et al., 1998; CASIMIR, Jorde et al., 2000; MesoHabsim, Parasiewicz, 2001, 2007; Vezza et al., 2015; MEM, Hauer et al., 2007). For instance, such methods have been widely used for viewing the ecohydraulic impacts of flow regulation (Maddock et al., 2013). Various hydromorphological and habitat indices have also been developed, providing a quantitative assessment of spatiotemporal habitat variability (e.g., HDMI, Gostner et al., 2013; IHQ and IHSD, Vezza et al., 2015).

Finally and most recently, frameworks for the delineation and analysis of geomorphic units have been devised based upon fluvial geomorphology theory (e.g., Brierley et al., 2013; Wyrick and Pasternack, 2014; Wheaton et al., 2015). For example, Brierley et al. (2013) provided an overall guided, open-ended procedure for the analysis of geomorphic units following a question-based approach that allows a flexible interpretation of geomorphic units in terms of forms, formative processes, and control factors. In contrast, Wheaton et al. (2015) described a guided framework for identifying and mapping geomorphic units based on specific characteristics such as topographic thresholds, unit shape, and specific morphological attributes (e.g., unit position, sediment, and vegetation characteristics).

Although a relationship between river physical and biological components is increasingly recognised (Maddock et al., 2013), this remains poorly understood, mainly because existing methods for the survey of physical habitat characteristics and conditions are still limited in their application, especially at scales that are spatially and temporally significant for physical and biological processes (Friberg et al., 2011). Because geomorphic units constitute the physical structures that underpin habitat units, an assessment of the assemblage of geomorphic units is needed to provide information about the range of existing habitats occurring in a given reach and repeated assessments can reveal their dynamics. Therefore, systematic procedures to collect and interpret information on geomorphic units and physical habitats at appropriate spatial scales and based on contemporary fluvial geomorphic understanding are needed. Procedures to assess physical habitats need to be ecologically and geomorphologically meaningful, enabling ecologically relevant scales and physical variables to be placed into a geomorphological characterisation template (Brierley et al., 2013).

Recently, new approaches have been developed or extended within the REFORM (REstoring rivers FOR effective catchment Management) project, funded by the European Union's FP7 Programme. Specifically, a set of hydromorphological assessment procedures have been devised incorporating clearly defined stages and steps, which support the assessment of river conditions in a consistent manner (Rinaldi et al., 2015a, 2015b, 2016a). The geomorphic unit survey and classification system (GUS; Belletti et al., 2015b; Rinaldi et al., 2015b) integrates and completes these procedures, placing the focus on the geomorphic unit scale to provide classification, characterisation, analysis, and monitoring of the set of geomorphic units present in a given reach. The GUS was developed within REFORM. The Italian version, named SUM (Sistema di rilevamento e classificazione delle Unità Morfologiche), is part of the broad Italian system for river hydromorpholgical assessment, analysis, and monitoring (IDRAIM; Rinaldi et al., 2015c) whose national guidelines have been published by the Italian National Institute for Environmental Protection and Research (ISPRA; Rinaldi et al., 2015d).

This paper presents and synthetically describes the GUS and summarises its main applications. First (Section 2), we present the GUS, including the rationale behind it, its main characteristics and aims, its structure, and the methodological approach, as well as the guidebook of the main river geomorphic units that can be found in a wide range of river types across the world. We also provide some maps and pictures of an example application of the system. Second (Section 3), we discuss the GUS in the context of river classification and indicate how to apply the system in hydromorphological surveys and in supporting the analysis of the spatial and temporal variation of habitats for biota. We also critically discuss its weakness and identify future research challenges.

2. The geomorphic unit survey and classification system (GUS)

2.1. Rationale

The hierarchical view of river systems as described in the introduction is helpful for understanding process interactions within and between scales as well as river behaviour through time, providing important information that can support more effective river management. A recently developed nested hierarchical framework and its application to river management under the WFD is described by Gurnell et al. (2016a) and forms the basis for the method described in this paper.

In general, moving downstream through a fluvial system, different channel types (or patterns) and different associated geomorphic units may occur as a result of changing boundary conditions, such as valley and bedslope, discharge, sediment size, etc. (Rinaldi et al., 2016b). Despite this general rule, the assemblage may vary among biogeographical regions and may also be degraded or reduced by human disturbances (Rinaldi et al., 2016b).

Within a single geomorphic unit, smaller scale features can be distinguished, notably one to several hydraulic units (i.e., spatially distinct patches of relatively homogeneous surface flow and substrate character), each of which can include a series of river elements (i.e., individuals and patches of sediment particles, plants, wood pieces, etc.; Gurnell et al., 2016a). These spatial units are the most appropriate to assess the presence and diversity of physical habitats (Fig. 1). Geomorphic and hydraulic units generally correspond to the mesohabitat scale (about 10^{-1}–10^{3} m), whereas smaller spatial units (i.e., river elements) coincide with the microhabitat scale (~1–50 cm; Frissell et al., 1986; Bain and Knight, 1996; Kemp et al., 1999; Fausch et al., 2002; Thorp et al., 2006; Hauer et al., 2011; Parasiewicz et al., 2013; Zavadil and Stewardson, 2013).

2.2. Main characteristics and aims of the GUS

According to key concepts described above, this section summarises the main characteristics and aims of the GUS.

- GUS is designed to provide a general framework for the survey and classification of geomorphic units and is embedded within a more general spatially nested hierarchical framework as described by Gurnell et al. (2016a). It adopts a top-down approach to identify, characterise, and analyse the assemblage of geomorphic units within a given river reach.
- Spatial units within the GUS are organised and analysed at three spatial scales and three levels of characterisation, respectively.
- GUS is also supported by an extensive and exhaustive illustrated guidebook for the identification of the main geomorphic units that may be encountered. The guidebook covers a wide range of river types, from low energy lowland systems to high energy mountain systems, allowing for process-based classification of geomorphic units.
- Since the variability of geomorphic units is great between different river types, along the same river, and is affected by human impacts, the GUS does not aim to assess deviation from any reference conditions and/or to assess the status or quality of the stream by the use of synthetic indices.
- GUS is an open-ended, flexible framework, where the operator can establish the level of characterisation and the specific focus of the survey, depending on the survey objectives and on available resources.
- The results of the GUS support understanding of the morphology of a given reach, the analysis of river reach behaviour and evolution, and the understanding of interactions among river hydromorphological conditions at the reach scale, characteristic geomorphic units, and related biological conditions.

2.3. The spatial settings, scales, and levels of characterisation of the GUS

The overall spatial domain of application of the GUS is potentially the entire genetic floodplain, defined as the part of the valley floor delimited by hillslopes or ancient terraces that can be directly affected or potentially influenced by fluvial processes. However, the main focus of the survey is the portion of the fluvial corridor that is most directly or frequently connected with contemporary fluvial processes. This corresponds to the relatively natural corridor, which, when contemporary management permits, is occupied by spontaneous riparian vegetation (areas A and B, Fig. 2). Nonetheless, depending on the aims of the study, the survey can be extended to human-dominated portions of the floodplain (agricultural lands, urbanised areas; area C, Fig. 2).

Within this river corridor geomorphic units are organised in two spatial settings: (i) the bankfull channel (i.e., inundation frequency below 1 ÷ 3 years), which includes units that are mostly submerged (e.g., bed configuration, submerged vegetation) and mostly emerged (e.g., bars, islands, large wood jams) at base flow, as well as features located within the bankfull channel margins at the interface with the floodplain (e.g., banks, benches; area A, Fig. 2); (ii) the floodplain, which comprises all the units occupying the floodplain (e.g., recent terraces, wetlands, natural levees; areas B and C, Fig. 2).

2.3.1. Spatial scales

Within the GUS, geomorphic units are organised within different levels that are embedded into a nested hierarchical framework. The levels differ in terms of spatial scale (i.e., size) and detail of characterisation (Section 2.3.2) such that larger spatial scales are related to broad levels of analysis, whereas smaller spatial scales are associated with more detailed levels of characterisation. The three spatial levels are as follows:

- Macro-unit. The coarse assemblage of units of the same type, mainly water, sediment, vegetation (Fig. 3). The minimum size of a macro-unit is the size of the contained unit (e.g., a bar, an island) when the macro-unit only incorporates a single unit.
- Unit. This is the basic spatial unit of the GUS and corresponds to a feature with distinctive morphological characteristics and significant size (e.g., riffle, bar, island, recent terrace, oxbow lake, etc.; Fig. 4A–D) located within a macro-unit. This is the spatial scale that defines the pieces of the mosaic that characterise river morphology at the reach scale. More accurate criteria for the definition of such units within the GUS depend on their nature (i.e., water, sediment, or vegetation units), the spatial setting, and their location within the river corridor (Rinaldi et al., 2015b).
- Sub-unit. A relatively small patch with fairly homogeneous characteristics in terms of vegetation, sediment, or flow conditions located within a unit (e.g., backwater areas, ramps, isolated woody plants, small vegetated patches, etc.; Fig. 4E, F).

All three levels of spatial unit can be analyzed at the reach or subreach scale (Fig. 3B and C, respectively), where the latter is a portion of a reach that contains assemblages of geomorphic units that characterize the morphology of the reach in which the subreach is located. However, macro-units are usually analysed at the reach scale, whereas units and sub-units are most commonly analysed at the subreach scale.

Five near-natural macro-units have been defined within the GUS (Fig. 3), each of them includes a range of unit types. (i) *Base-flow* or *submerged channels* include all geomorphic units ($n = 8$ types) that are found within the bankfull channel and are submerged at base flow (e.g., cascade, riffle, etc.). (ii) *Emergent sediment units* can contain all geomorphic units ($n = 9$ types) located within the bankfull channel that are mostly exposed at base flow (e.g., mid-channel bar, bedrock outcrop, etc.). (iii) *In-channel vegetation* comprises all geomorphic features ($n = 5$ types) of significant size that are dominated by vegetation (e.g., islands, vegetated banks, etc.). (iv) The *riparian zone* is the portion of the floodplain affected by fluvial processes (e.g., channel mobility, flooding) and characterised by spontaneous riparian vegetation or relatively natural conditions. It includes nine types of units of different elevation (e.g., levée, ridges, and swales, etc.). (v) *Floodplain aquatic zones* identify the presence of water within the floodplain and include two types of unit (floodplain lakes and wetlands). The portion of the overall floodplain beyond the *riparian zone* that is dominated by human elements or activities (urbanised areas, infrastructures, agriculture) is included within an additional macro-unit *human-dominated areas*.

Some types of units can be further subdivided into subtypes at a greater level of detail (see Section 2.3.2; e.g., *longitudinal bar* and *diagonal bar* are subtypes of *mid-channel bar* unit).

In total 33 types of units (35 including macro-unit types) and 59 subtypes of units (63 including subtypes of macro-units) are defined within the GUS.

Each type of macro-unit and unit has an identification code. For units, this is composed of the macro-unit code plus the relevant unit code (e.g., EC represents mid-channel bar, incorporating the macro-unit E for emergent sediment units). Subtypes of units are identified by the unit type code plus a progressive number for mapping purposes. Sub-units are spatially associated with unit types.

The GUS also incorporates artificial features (e.g., check-dams, groynes, ripraps). These are not considered to be macro-units, units, or sub-units, but they are important elements of the fluvial landscape because of their significant impact on fluvial processes and on the morphology and assemblage of geomorphic units. These features are recorded separately as ‘artificial elements’ regardless of their location within the river corridor (i.e., bankfull, floodplain). Artificial elements

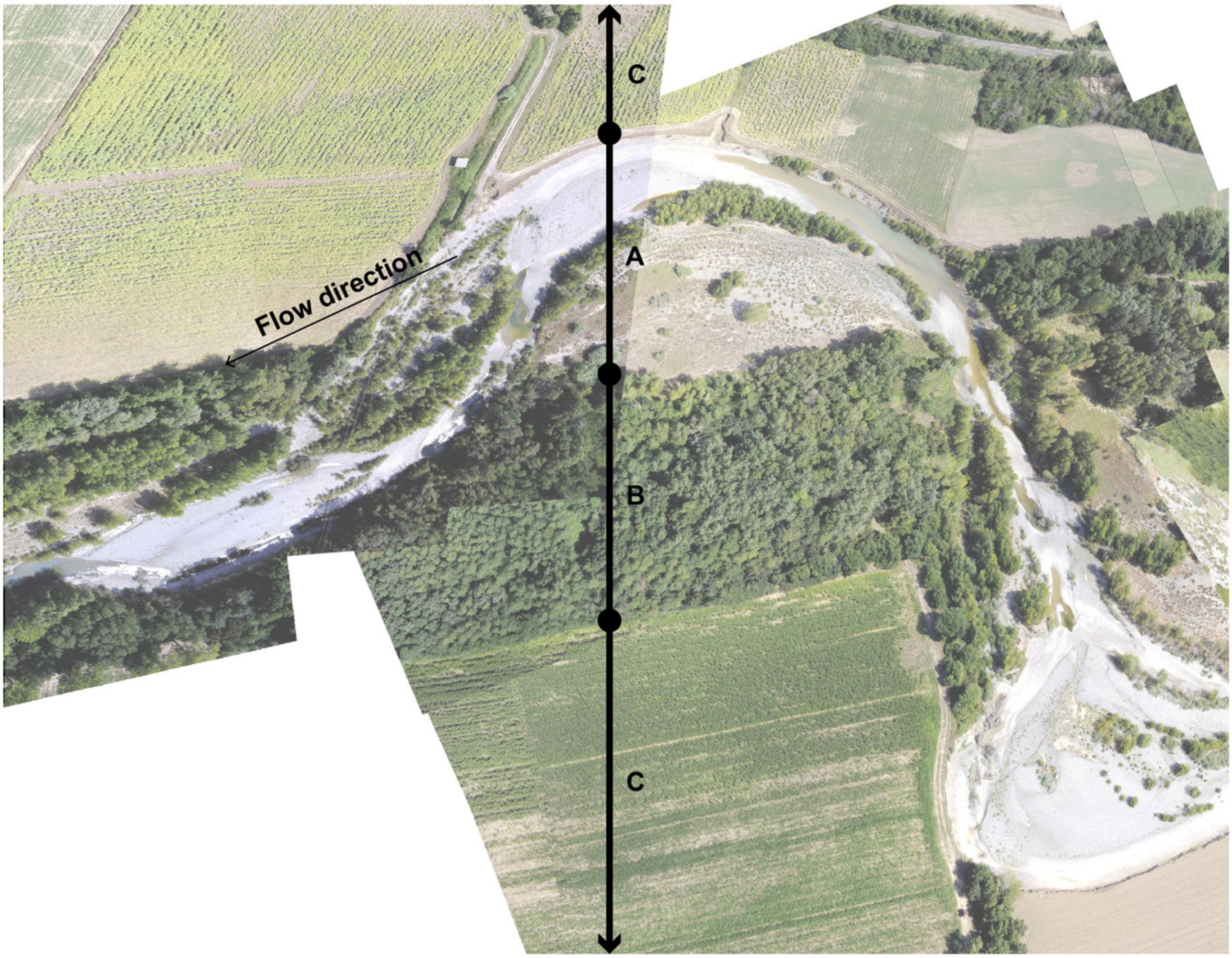


Fig. 2. Spatial settings of the GUS. (A) Bankfull channel; (B + C) floodplain; (A + B) natural corridor; (C) human-dominated areas.

are delineated at the broad level and then characterized at the basic level (see Section 2.3.2).

2.3.2. Levels of characterisation

Within the GUS, geomorphic units can be surveyed according to three different levels of analysis as follows (Table 1):

- Broad level. This corresponds to the delineation and a general characterisation of macro-units (Fig. 3C), in terms of presence/absence, areal extent or percentage cover within the two spatial settings (i.e., bankfull channel, floodplain).
- Basic level. A complete delineation and first level of characterisation of all types of geomorphic units, in terms of presence/absence, number, area, or length (Figs. 4B and 5). Some macro-unit types can also be described at this level (i.e., main and secondary channels).
- Detailed level. This (i) provides more detailed information and data for geomorphic units (and some macro-units) on genetic processes, morphological, hydrological, vegetation and sediment properties; (ii) describes macro-unit and unit subtypes (when applicable); and (iii) characterises sub-units.

2.4. Survey methods and procedures

Remote/proximal sensing techniques and field survey can be used to identify the units. The two approaches are generally used in synergy, but in some cases it may only be possible to use one of these, depending on the selected level of characterisation, the size of the river, and the resolution of the available remotely sensed data and imagery. The delineation of macro-units at the broad level is entirely based on remotely/proximally sensed data sources, analysed within a GIS software. Therefore, it typically can be applied to rivers of sufficient size (usually having channel width > 30 m) but the limits depend on the resolution and quality of the available imagery. Characterisation at the basic level is mainly carried out by field survey, but remote sensing and GIS analysis can also be used for large rivers or where very high spatial resolution imagery is available. The detailed level is always carried out by field survey.

For remote sensing, aerial photos of sufficient resolution are usually needed. Satellite images of lower resolution (e.g., Google earth images) can be used for preliminary reconnaissance of morphological characteristics, but the delineation of macro-units and units within a GIS requires higher spatial resolution photographs and LiDAR data, which is especially useful for defining floodplain units (e.g., distinguishing different elevations of recent terraces) and emergent units within the bankfull channel (e.g., bars, benches, and high bars). The increasing development of remote/proximal sensing platforms (i.e., UAV), sensors and techniques such as ultra-light systems, bathymetric LiDAR, structure from motion photogrammetry, hyperspectral imaging systems as well as recent and upcoming high resolution satellite data sets (e.g., Carbonneau and Piégay, 2012; Bizzi et al., 2016) will very likely lead to their increasing use for characterising geomorphic units, although a simultaneous check and their geomorphological interpretation in the field is strongly recommended.

The field survey at the basic and detailed levels is based on a series of survey forms (see below) and can be supported by available

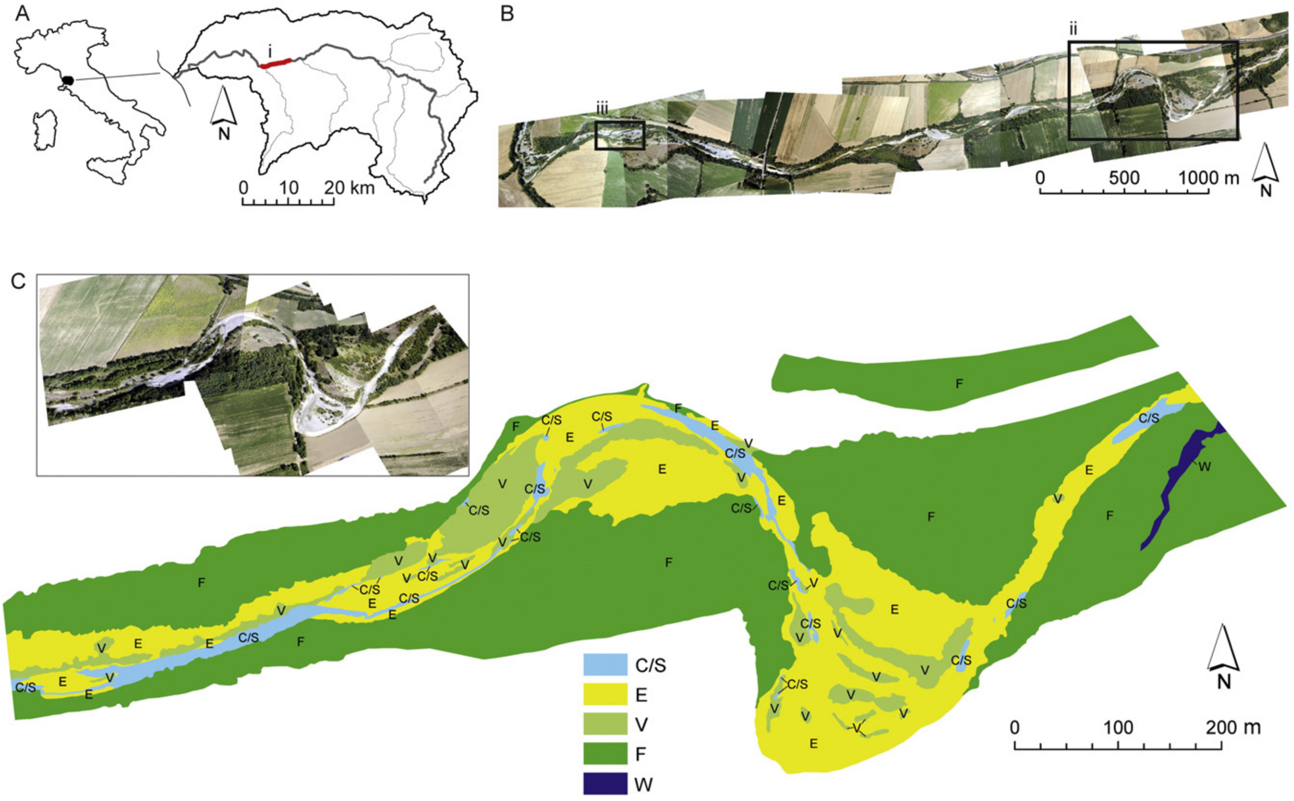


Fig. 3. Examples of macro-units for a subreach of the Cecina River, Italy. (A) Location of the studied reach (i) displayed in (B) within the Cecina River catchment. (B) Aerial photo of the analysed reach (i) and location of the subreach (ii) mapped in (C) and detailed in Fig. 6, and subreach (iii) detailed in Fig. 4. (C) Map of the macro-units for the subreach (ii) at the broad level: C/S, baseflow or submerged channels; E, emergent sediment units; V, in-channel vegetation; F, riparian zone; W, floodplain aquatic zones.

topographic instruments (e.g., GPS) as well as mobile mapping techniques and tools (e.g., QGIS Mobile). It is recommended that field survey proceeds from upstream to downstream, focusing in turn on different spatial settings (i.e., bankfull channel, floodplain), particularly for large rivers. According to the objectives, the field survey may be conducted by one surveyor when only presence/absence and number of units is

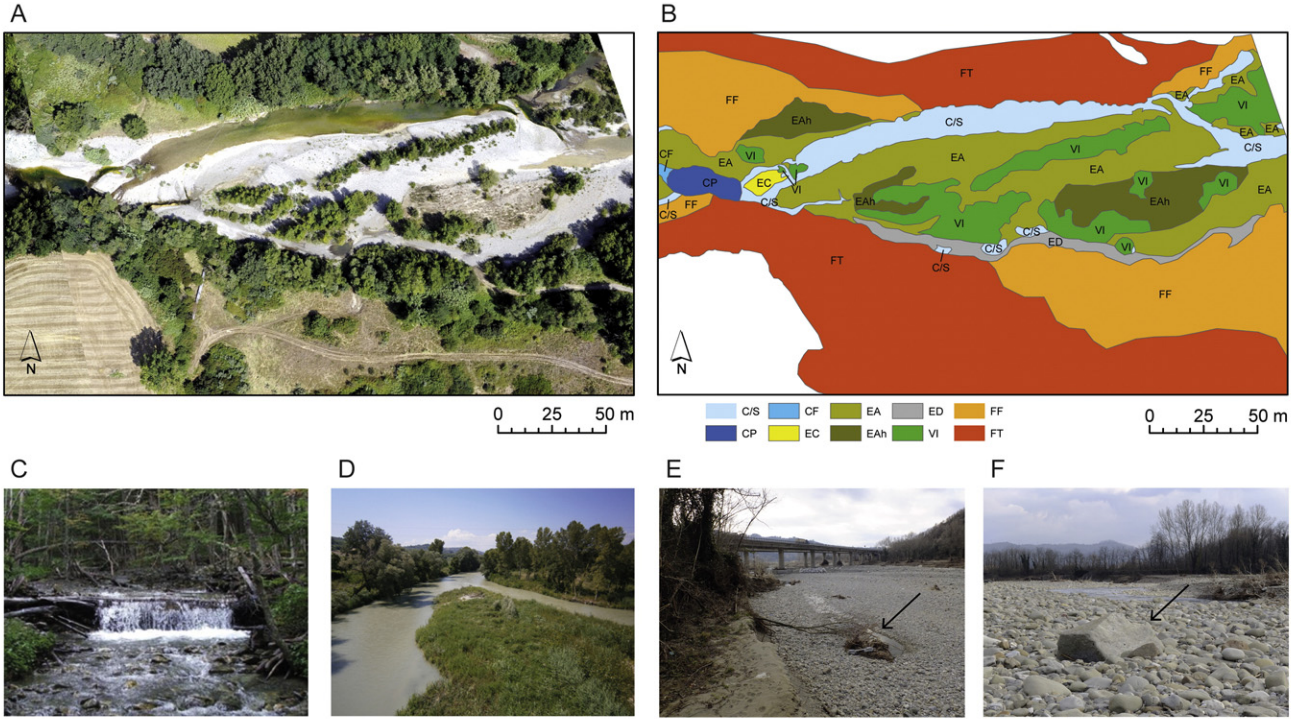


Fig. 4. Subreach (iii) (see Fig. 3 for location) illustrating GUS units and sub-units. (A) Aerial image of the subreach. (B) Map of geomorphic units within the subreach (see Fig. 6 for explanation of the unit codes). (C) A log-step unit. (D) A grassy island unit. (E) A small wood accumulation sub-unit. (F) An isolated boulder sub-unit.
(Source: A and B modified from Rinaldi et al., 2016a; C and D from Rinaldi et al., 2015b; E and F from Belletti et al., 2015c).

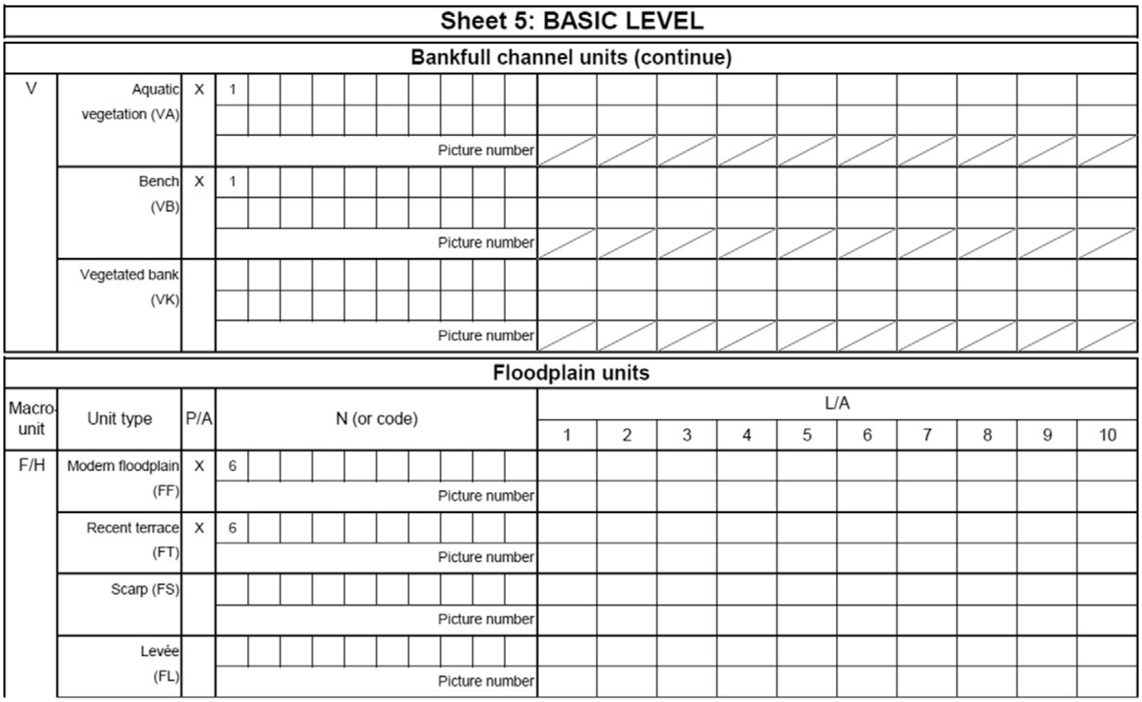
Table 1
The units investigated, methods used, types of information collected, and characterisation achieved at the three different levels of application of the GUS.

	Broad	Basic	Detailed (optional)
Spatial unit	Macro-units	Macro-units (some) Units	Macro-units (some) Units Sub-units
Method	Remote sensing	Field survey Remote sensing (when possible)	Field survey
Type of collected information	Presence/absence (minimum level)	Presence/absence (minimum level)	Presence/absence (Subtypes/sub-units)
	Area (optional) (necessary for application of GUS sub-indices)	Number (minimum information for application of GUS indices)	Number
			Formative processes, morphological characteristics, hydraulic conditions, vegetation type, sediment
	Frequency (%) (optional)	Linear or areal extension (%) (optional)	Specific measures
Applications	Required for large rivers (all morphologies)	Required for single-thread and small rivers	Always optional
	Required for unconfined/partly confined large rivers (floodplain units)	Optional for multi-thread and transitional channels (always required for application of GUS indices)	

required, but by at least two surveyors if unit sizes (length or area) need to be measured. Field surveys should be conducted during low-flow periods because they are safer, give a better visibility of submerged units (as well as the actual boundaries of mostly emerged units such as bars), and also because macro-units at the broad level are most consistently identified during low-flow conditions. Partially or totally dry conditions should be avoided, except in the case of intermittent or temporary streams (see below), because they impede the classification of submerged units. However, depending on the survey objectives, surveys under a range of different flow conditions may be informative (see Section 3.3). In the case of intermittent or temporary streams, the field survey is carried out during periods that represent the dominant hydrological regime conditions, and in any case under the same conditions experienced during the remote, broad level analysis.

The survey is carried out by completing a set of 16 survey sheets. These sheets are mainly designed to support and guide field survey and so should be used in a way that fits the objectives of the study. The first sheet (survey plan) helps to organize the survey in the context of its objectives, by recording (i.e., using a *tick*) the kinds of information that are to be collected (i.e., which spatial setting, which level, and which spatial scale). The second sheet records general information about the river, the surveyed reach and subreach (e.g., reach/subreach length, location, reach slope, width, morphology, hydrological regime etc.) and provides a space for a general field sketch. The remaining sheets are the core of the survey. They list all 35 units and 63 unit subtypes that may be surveyed (broad, basic, and detailed levels). Fig. 5 shows an extract of a compiled sheet for the survey of geomorphic units at basic level.

The main results of the GUS at broad, basic, and detailed levels are three maps for macro-units, units, and unit subtypes (including sub-units, when relevant), respectively (e.g., Fig. 3C maps macro-units). According to the survey level and rules (see Table 1 and Section 2.3.2), the macro-unit and unit maps may also contain information on the spatial extent of features (areal or linear). The map for the detailed level may contain additional information on unit characteristics (e.g., sediment and vegetation characteristics, hydraulic conditions) as well as displaying sub-units. These maps can be processed to obtain multi-level maps that combine the information collected (e.g., Fig. 6 maps



Sheet 5: BASIC LEVEL

Bankfull channel units (continue)

V	Aquatic vegetation (VA)	X	1										
			Picture number										
	Bench (VB)	X	1										
			Picture number										
	Vegetated bank (VK)												
			Picture number										

Floodplain units

Macro-unit	Unit type	P/A	N (or code)	L/A									
				1	2	3	4	5	6	7	8	9	10
F/H	Modern floodplain (FF)	X	6										
			Picture number										
	Recent terrace (FT)	X	6										
			Picture number										
	Scarp (FS)												
			Picture number										
	Levée (FL)												
			Picture number										

Fig. 5. Extract of a field sheet for the survey of units at basic level. It displays parts of the in-channel vegetation units and part of the floodplain units recorded for the example reported in Fig. 6.

unit types and subtypes surveyed at basic and detailed levels, respectively).

The time required to apply the GUS on a single reach (or subreach) depends on many factors, including the expertise and experience of the operator, the availability of necessary information and materials (particularly aerial photographs at good resolution) and the length and area of the reach. Approximately 1–3 days are required to survey one or more subreaches within a single reach, including desk- and field-based survey; but this time may be significantly reduced when surveying rivers with a simple and relatively uniform channel morphology and may increase when surveying large rivers or those with a complex channel morphology (e.g., braided or wandering reaches).

Figs. 3 and 6 illustrate an application of the GUS at broad and basic levels, respectively, for an unconfined reach that flows within a relatively narrow floodplain in the middle to lower portion of the Cecina River, central Italy (location shown in Fig. 3A). The channel is classified as sinuous with alternate bars, a gravel bed, a mean slope of ~0.003, and a mean width of about 50 m. The reach is classified to be in good morphological condition (Rinaldi et al., 2016a). The survey of macro-units at the broad level was carried out for the entire reach length (6.5 km) and for two subreaches (about 1.5 km) by remote sensing. The survey of geomorphic units at the basic level was carried out at the subreach scale using high resolution aerial photos (15 cm) images followed by a field survey to better delineate the units and their subtypes. In particular, the field survey was useful in identifying and delimiting a bench (VB) within the bankfull channel and in more precisely defining topographic differences between the modern floodplain (FF) and recent terraces (FT). Fig. 6 shows an example of the output of the survey, including basic and detailed level classification of geomorphic units at the subreach scale. The approximate time taken to produce the map in Fig. 6 was one day for the image analysis, including the processing of raw images (georeferencing and mosaicking) and post-field corrections, and a half a day for the field survey.

2.5. The GUS illustrated guidebook

Geomorphic units, related macro-units, and subtypes as well as examples of sub-units, are described in an illustrated guidebook (Rinaldi et al., 2015b). Each spatial unit is described in the form of a box (e.g., Fig. 7) that gives the name of the unit; the identification code (for unit and macro-unit types); the main references that describe the unit type; a short but complete definition, including the river types where the unit is more likely to be found; distinctive characteristics compared to similar units; a picture and a sketch; some examples of equivalent terms. Similar definitions and descriptions of the main unit subtypes are also provided. For example, in the case of the unit *bank-attached bar*, descriptions of subtypes of units such as *side bar* or *point bar* or *counterpoint bar*, etc. (e.g., Table 2) are included. In this example, the unit *bank-attached bar* is delineated at the basic level, whereas the subtypes can be identified at the detailed level.

The guidebook permits us to distinguish units under a consistent classification scheme, according to their nature, their spatial setting, and their position within the river corridor (e.g., water vs. sediment; floodplain vs. bankfull; mid-channel vs. bank-attached), and the processes that led to their formation (e.g., a *forced riffle* is formed by bedrock outcrops, accumulation of coarse sediments, or large wood elements).

The guidebook also provides a list and short description of some examples of sub-units as well as a list of the main artificial features that may be encountered.

All geomorphic units included within the guidebook are built on a sound fluvial geomorphology background and take into account recent progress in river science research (e.g., Surian et al., 2009; Comiti and Mao, 2012; Buffington and Montgomery, 2013; Fryirs and Brierley, 2013; Gurnell, 2014; Gurnell et al., 2014; Rinaldi et al., 2016b).

2.6. The analysis of geomorphic units: GUS indices

In order to provide a consistent analysis of geomorphic units mapped, classified, and characterised through the GUS, two synthetic indices have been developed that use information from the survey of the geomorphic units. The two GUS indices (GUSI) describe the spatial heterogeneity of a given reach in terms of geomorphic units and can be used (i) to better characterise the assemblage of geomorphic units, and (ii) to monitor the trend of changes in geomorphic units in a given reach, in terms of a decrease or increase in richness and density of geomorphic units. Such changes may reflect natural morphological dynamics or they may indicate impacts of pressures or interventions. The results obtained by applying the GUS and its indices at the subreach or reach scale need to be combined with a morphological assessment at reach-scale (e.g., the MQI; Rinaldi et al., 2013, 2016a) to properly interpret the significance and relevance of the composition and heterogeneity of geomorphic units. This means that high or low values of the indices (e.g., more or less geomorphic units) are not meaningful in absolute terms, but the indices help to summarize results and facilitate comparison for management purposes (e.g., monitoring).

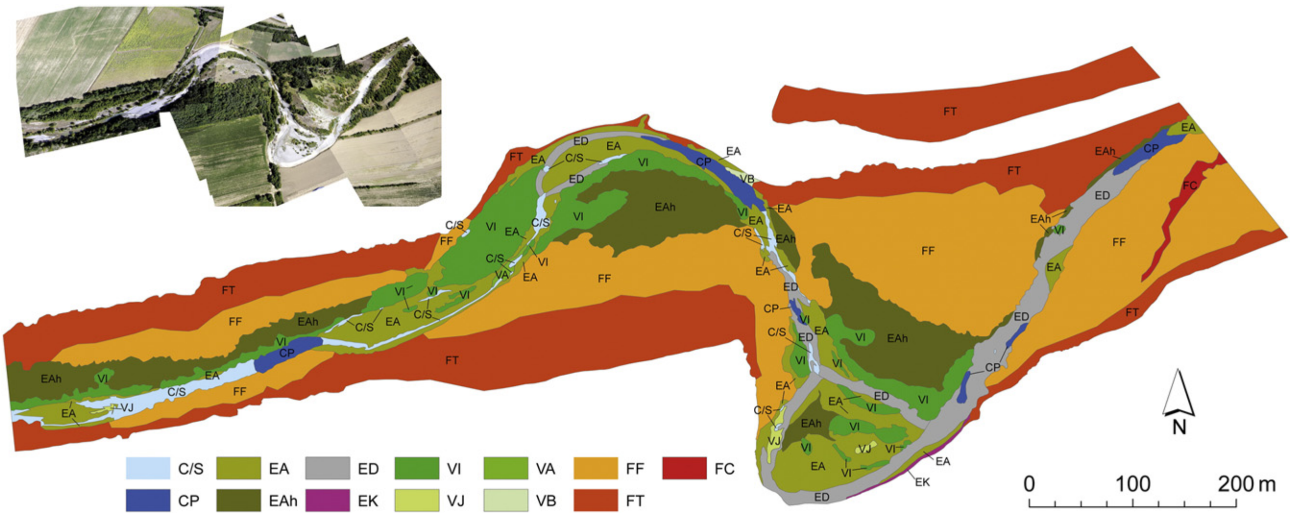
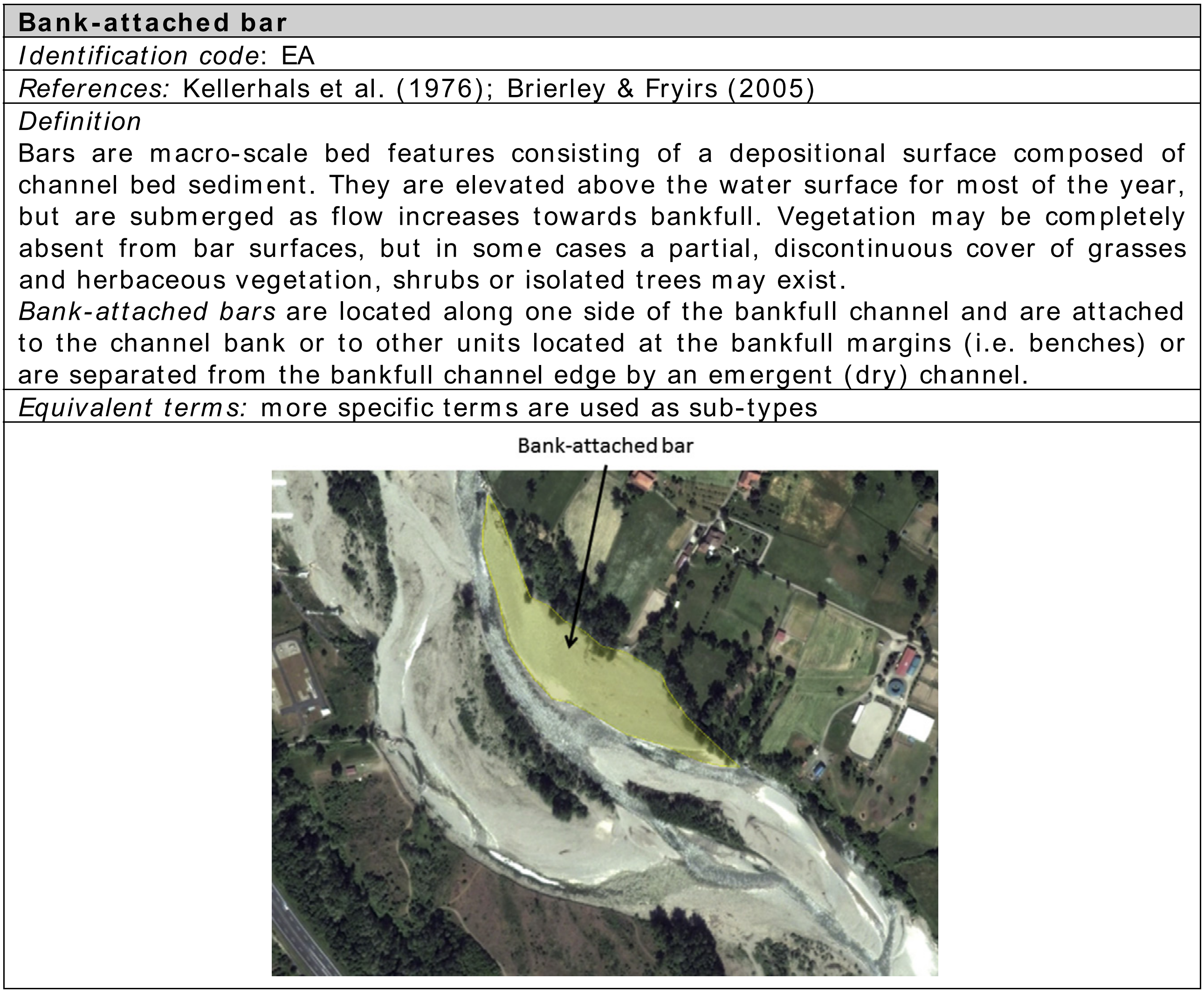


Fig. 6. Application of the GUS (basic level) to a subreach (subreach (ii) in Fig. 3) of the Cecina River, showing an aerial image of the subreach and a map of the types of geomorphic units present (C/S, base flow/secondary channels; CP, pool. EA, bank-attached bar; EAh, bank-attached high bar; ED, dry channel; EK, unvegetated bank; VI, island; VJ, large wood jam; VA, aquatic vegetation; VB, bench; FF, modern floodplain; FT, recent terrace; FC, secondary channel (within the floodplain)).



Bank-attached bar

Identification code: EA

References: Kellerhals et al. (1976); Brierley & Fryirs (2005)

Definition

Bars are macro-scale bed features consisting of a depositional surface composed of channel bed sediment. They are elevated above the water surface for most of the year, but are submerged as flow increases towards bankfull. Vegetation may be completely absent from bar surfaces, but in some cases a partial, discontinuous cover of grasses and herbaceous vegetation, shrubs or isolated trees may exist.

Bank-attached bars are located along one side of the bankfull channel and are attached to the channel bank or to other units located at the bankfull margins (i.e. benches) or are separated from the bankfull channel edge by an emergent (dry) channel.

Equivalent terms: more specific terms are used as sub-types

Fig. 7. Example of a box from the GUS guidebook providing the definition of a *bank-attached bar* geomorphic unit.
(Sorce: from Rinaldi et al., 2015b).

2.6.1. Geomorphic Units Richness Index (GUSI-R)

The Geomorphic Units Richness Index (GUSI-R) evaluates how many types of geomorphic units and macro-units (e.g., bar, island, riffle, secondary channel) are observed within a given reach in comparison with the maximum number of possible units:

$$\mathrm{GUSI-R} = \Sigma\, NT_{GU}/n \qquad (1)$$

where NT_{GU} is the total number of types of units and macro-units within the investigated reach (or subreach; e.g., where riffles, pools, and side bars are present, $NT_{GU} = 3$), whereas n is the total number of possible types of units and macro-units, i.e., 35.

For the calculation of this index, the presence/absence of each type of unit is required (carried out at the basic level of survey).

Table 2
Subtypes of *bank-attached bar* within the GUS (see Fig. 7 for definition; the GUS terms and the key references used to provide the definition within the GUS are reported, as well as other terms employed in the literature, which are reported in the guidebook as *equivalent terms*).

GUS terms	Other terms
Side bar (Kellerhals et al., 1976; Church and Jones, 1982; Hooke, 1995)	*Lateral bar, alternate bar* (Thorne, 1998) *Bank-attached or attached bar* (Hooke, 1995) *Lateral bar* (Wheaton et al., 2015)
Point bar (Kellerhals et al., 1976; Church and Jones, 1982; Hooke, 1995; Thorne, 1998)	/
Counterpoint bar (Thorne and Lewin, 1979; Page and Nanson, 1982; Lewin, 1983; Hickin, 1984)	*Concave bar* (Hooke, 1995)
Junction bar (Kellerhals et al., 1976; Thorne, 1998)	*Tributary confluence bar* (Brierley and Fryirs, 2005)
Forced bank-attached bar (Brierley and Fryirs, 2005)	/

2.6.2. Geomorphic Units Density Index (GUSI-D)

The Geomorphic Units Density Index (GUSI-D) calculates the total number of geomorphic units (independent of type) within the investigated reach per unit length:

$$\mathrm{GUSI-D} = \Sigma\, N_{GU}/L \qquad (2)$$

where N_{GU} is the total number of geomorphic units observed along the investigated reach (or subreach; e.g., in the case of 7 riffles, 6 pools, and 3 bars, $N_{GU} = 16$), whereas L is the length (in km) of the investigated reach (or subreach).

The calculation of this index requires the number of units and macro-units of each type to be measured (this is carried out at the basic level of survey).

2.6.3. Sub-indices

The method allows a series of sub-indices to be calculated, expressing the abundance and density of geomorphic units for each spatial setting, i.e., bankfull channel and floodplain. The following richness and density sub-indices are defined:

$$\mathrm{GUSI}-\mathrm{R}_{\mathrm{BC}} = \Sigma\, NT_{BCGU}/n \tag{3}$$

$$\mathrm{GUSI}-\mathrm{R}_{\mathrm{FP}} = \Sigma\, NT_{FPGU}/n \tag{4}$$

$$\mathrm{GUSI}-\mathrm{D}_{\mathrm{BC}} = \Sigma\, N_{BCGU}/n \tag{5}$$

$$\mathrm{GUSI}-\mathrm{D}_{\mathrm{FP}} = \Sigma\, N_{FPGU}/n \tag{6}$$

where GUSI-R_{BC} is the richness sub-index of bankfull channel geomorphic units, NT_{BCGU} is the total number of types of bankfull channel geomorphic units, GUSI-R_{FP} is the richness sub-index of floodplain geomorphic units, NT_{FPGU} is the total number of types of floodplain geomorphic units, GUSI-D_{BC} is the density sub-index of bankfull channel geomorphic units, N_{BCGU} is the total number of bankfull channel geomorphic units (independent of the type), GUSI-D_{FP} is the density sub-index of floodplain geomorphic units, and N_{FPGU} is the total number of floodplain geomorphic units (independent of the type).

Lastly, a series of sub-indices expressing the density of geomorphic units for each macro-unit can be calculated. The calculation requires measurements of the area of each macro-unit (this is carried out at the broad level). The sub-indices are defined as follows:

$$\mathrm{GUSI}-\mathrm{D}_{\mathrm{C}} = \Sigma\, N_{CGU}/A_C \tag{7}$$

$$\mathrm{GUSI}-\mathrm{D}_{\mathrm{E}} = \Sigma\, N_{EGU}/A_E \tag{8}$$

$$\mathrm{GUSI}-\mathrm{D}_{\mathrm{V}} = \Sigma\, N_{VGU}/A_V \tag{9}$$

$$\mathrm{GUSI}-\mathrm{D}_{\mathrm{F}} = \Sigma\, N_{FGU}/A_F \tag{10}$$

$$\mathrm{GUSI}-\mathrm{D}_{\mathrm{W}} = \Sigma\, N_{WGU}/A_W \tag{11}$$

where, for bankfull channel macro-units, GUSI-D_{C} is the density sub-index of base-flow channel geomorphic units, N_{CGU} is the number of base-flow channel geomorphic units, A_C is the area (in km^2) of the base-flow channel macro-unit, GUSI-D_{E} is the density sub-index of emergent sediment geomorphic units, N_{EGU} is the number of emergent sediment geomorphic units, A_E is the area (in km^2) of the sediment emergent macro-unit, GUSI-D_{V} is the density sub-index of in-channel vegetation geomorphic units, N_{VGU} is the number of in-channel vegetation geomorphic units, A_V is the area (in km^2) of the in-channel vegetation macro-unit; for floodplain macro-units, GUSI-D_{F} is the density sub-index of riparian zone geomorphic units, N_{FGU} is the number of riparian zone geomorphic units, A_F is the area (in km^2) of the riparian zone geomorphic units, GUSI-D_{W} is the density sub-index of floodplain aquatic zones geomorphic units, N_{WGU} is the number of floodplain aquatic zones geomorphic units, A_W is the area (in km^2) of floodplain aquatic zones macro-unit.

Table 3 summarises the results of applying the GUS indices and sub-indices to the subreach shown in Fig. 6.

Table 3
Summary of the GUS indices and sub-indices obtained for each (a) spatial setting and (b) macro-units of the subreach shown in Fig. 6 (GUSI-R, geomorphic units richness index; GUSI-RBC, richness sub-index for the bankfull channel; GUSI-RFD, richness sub-index for the floodplain; GUSI-D, geomorphic units density index; GUSI-DBC, density sub-index for the bankfull channel; GUSI-DFD, density sub-index for the floodplain; GUSI-D_{C}, density index for the baseflow channel; GUSI-D_{E}, density index for the emergent sediment units; GUSI-D_{V}, density index for the in-channel vegetation; GUSI-D_{F}, density index for the riparian zone).

(a) GUS indices and sub-indices for each spatial setting

Indices and sub-indices	Values
GUSI-R	0.40
GUSI-R_{BC}	0.31
GUSI-R_{FP}	0.09
GUSI-D	65.33
GUSI-D_{BC}	56.67
GUSI-D_{FP}	8.67

(b) GUS sub-indices for each macro-unit

Sub-indices	Values
GUSI-D_{C}	2988.3
GUSI-D_{E}	558.7
GUSI-D_{V}	1256.1
GUSI-D_{F}	85.7

3. Discussion: the GUS and the analysis of river hydromorphology and physical habitats

The analysis of geomorphic units through application of the GUS represents one of the steps required for a comprehensive analysis of river conditions. The data and information collected through the GUS should be integrated and interpreted within a broader and more general spatiotemporal context in order to understand the character and behaviour of geomorphic units within a given river system (e.g., Brierley et al., 2013). In this way it would be possible to assess overall river conditions and guide effective river management. Indeed, geomorphic maps based on geomorphic units provide a template to interpret and quantify process relationships and their controls, to evaluate river change, and to assess evolutionary trajectories (Wheaton et al., 2015).

This section discusses the contribution of the GUS in terms of river geomorphic units in the field of river classification, presents some potential applications of the method, and summarises weakness and future challenges to improve its application.

3.1. The GUS and the classification of river geomorphic units

River classification is a well-known issue in river geomorphology and is relevant to several applications (see for instance Rinaldi et al., 2016b). In this context, the hierarchical approach, the survey system, and the illustrated guidebook for geomorphic units described in this paper are in line with recent progress in fluvial geomorphology.

Compared to recent methodological frameworks for the identification and classification of geomorphic units (e.g., Wheaton et al., 2015), the GUS does not use specific topographic, hydraulic, or sedimentary thresholds to identify geomorphic units. However, the GUS provides a detailed guidebook concerning the main geomorphic units that can be found in a large range of river types, as well as a rational, process-oriented guided system for the delineation, classification, and analysis of geomorphic units. In particular, it consists of (i) an illustrated guidebook for the identification of 35 types plus 63 subtypes of geomorphic units (including macro-units) compiled by a group of fluvial geomorphologists, covering a wide range of sub-domains and thus of types of units (e.g., vegetation, bed configuration, sedimentary units) and types of rivers (e.g., lowland systems, mountain systems, highly dynamic systems, etc.); and (ii) a system for unit survey based on a spatially-nested hierarchical framework that includes three spatial scales associated with three levels of characterization.

The guidebook (i), which resulted from an extensive review of existing and consolidated literature, combines the knowledge inherited from the long tradition on river classification to recent progress for example in the study of steep mountain systems (e.g., Comiti and Mao, 2012) and in the study of the interaction between vegetation and physical processes (e.g., Gurnell et al., 2016b). The guidebook also includes a wide range of vegetation units that are usually poorly considered by classic river classification approaches (e.g., benches, berms, and shelves). A clear, process-based definition and description of distinctive characteristics of each unit is reported (e.g., genetic processes, topographic or sedimentary characters, presence of vegetation), as well as equivalent terms adopted by different authors for equivalent units worldwide.

The GUS system (ii) adopts a top-down approach. The delineation of units is provided at first accounting for their nature and their location within the river corridor (i.e., sediment, water, or vegetation and bankfull vs. floodplain, respectively). The definition of each unit is then contextualised within the river type to which it belongs, and thus it includes the interpretation of processes. The distinction between 'main' and 'secondary' geomorphic units (unit types and subtypes, respectively) is also consistent with the hierarchical structure of the survey system that considers different levels of survey detail according to survey aims. This represents a good compromise and a considerable effort in order to embrace similar unit descriptions under a common classification scheme that accounts for process-based classification (e.g., *side bar* and *point bar* are subtypes of *bank-attached bars* formed under different conditions). Indeed, it often happens that different authors adopt different terms to describe similar or even the same spatial units, as illustrated in Table 2 for the unit *bank-attached bar*. Thus, although the mapping of river features, whether based on field or remote sensing surveys, may be subject to some subjectivity and accuracy, the GUS system and its guidebook help to achieve identification of distinctive geomorphic units linked to specific channel and river processes with a low margin of human error.

The system also foresees the delineation and characterization of a potentially unlimited number of smaller spatial units at a scale lower than those of geomorphic units, allowing links to be established with the biota (i.e., sub-units; see Section 3.3).

In the context of general frameworks for geomorphic unit analysis that consider forms, basic processes, and control factors (e.g., Brierley et al., 2013), the GUS fits well within them providing a first step for the survey and characterisation of geomorphic units. Indeed, the identification and delineation of geomorphic units within the GUS requires some interpretation of the processes that generated them (e.g., distinguishing between a modern floodplain and a recent terrace).

In summary, the GUS could be considered as complementary to frameworks such as those recently published by Brierley et al. (2013) and Wheaton et al. (2015). It provides detailed unit characterisation at different spatial scales (from landscape to a single river element) that can be adopted for many applications, as described in the following sections.

3.2. Characterising geomorphic units to understand river reach hydromorphology

The outputs from application of the GUS can be used for spatial and temporal analyses of geomorphic units to support understanding of river hydromorphology at the reach scale for a variety of aims, including:

- to provide a more detailed characterisation of the morphology at the reach scale, for example, to support the classification of the river type (e.g., the Extended River Typology; Rinaldi et al., 2016b);
- to support the analysis of morphological quality of the reach by integrating GUS with a morphological assessment method (e.g., the MQI; Rinaldi et al., 2013);
- as a monitoring tool, in order to detect small-scale morphological changes (e.g., the effect of different hydrological conditions) and to support the survey of the evolution of the morphology at the reach scale through time by integrating GUS with existing monitoring tools (e.g., the Morphological Quality Index for monitoring; Rinaldi et al., 2015c);
- to evaluate the effects of management actions on hydromorphology (e.g., after an intervention or restoration).

The outputs from applying the GUS can thus support different stages of the hydromorphological assessment framework developed within REFORM to achieve more effective river and catchment management (Rinaldi et al., 2015a, 2016a). In particular, the in-depth identification and characterization of problems at the scale of geomorphic units through application of the GUS in combination with the MQI and the MQIm can provide an overall assessment of river reaches that is useful for understanding their functioning and, therefore, for supporting the identification of appropriate management actions (see also Rinaldi et al., 2016a).

It is important to stress that the outputs of the GUS must be interpreted in combination with the results of a morphological assessment at the reach scale in order to better interpret the significance and relevance of the diversity of geomorphic units. Indeed, changes in the composition and number of geomorphic units depend on controls and processes acting at the reach or larger scales. For example, an increase in the abundance and diversity of geomorphic units in a given reach is not necessarily related to an improvement of morphological conditions but may be associated with the presence of artificial structures (e.g., weirs). On the contrary, a low diversity of geomorphic units can be the result of the *natural* simple geomorphic structure of a particular river type (e.g., a bedrock mountain channel; Rinaldi et al., 2016a). This is why the GUS indices do not aim to assess better or poorer river conditions. For example, in the case of the Cecina River reach, which displays good morphological conditions, the typical assemblage of geomorphic units at the subreach scale corresponds to what is expected for the type of channel morphology (sinuous with alternate bars); it comprises riffles, pools, glides, lateral bars (with occasional braiding), a highly sinuous low-flow channel, secondary channels, a modern floodplain, and recent terraces (Rinaldi et al., 2016a; Fig. 6). The GUS indices have been designed to reflect existing natural differences amongst river types, given that they account for all geomorphic units and thus river types together. Such differences are also apparent when sub-indices are compared for different spatial settings or macro-units within the same reach (Table 3). For example, the subreach in Fig. 6 shows a higher complexity of units in the bankfull (GUSI-R_{BC}) than in the floodplain (GUSI-R_{FP}) spatial setting, as expected for this quite dynamic type of river reach (Table 3). In contrast, the high density of channel units (GUSI-D_C) is the result of the hydrological stress conditions experienced by the river reach in this agricultural area.

The GUS is also a promising monitoring tool for observing the evolution of geomorphic units through time as a consequence of interventions or restoration, as well as in response to variable hydrological conditions under climate change. For these purposes, geomorphic units are first defined at base flow, corresponding to the flow conditions associated with the definition of units in the present work. Repeat surveys under low-flow conditions can establish changes through time, whereas survey under other flow conditions can help to observe the variation in unit extent, connectivity, etc. The results of application of the GUS can also be used to compare similar river types (for example, to evaluate the effects of different management actions) because similar river types usually display a similar range of geomorphic units thus enabling comparison of expected versus observed units.

3.3. The spatial and temporal variation of physical habitats for biota

The survey and classification of geomorphic units can support understanding of the links between hydromorphological conditions, ecological conditions, and biota because geomorphic units represent physical habitats for the flora and fauna that inhabit rivers. However, investigation of geomorphic units alone at a given time cannot provide information about the condition of physical habitats and thus the conditions for biota. Physical habitats in rivers show high turnover rates as well as high spatial heterogeneity in response to hydromorphological dynamics driven mainly by the hydrological regime (e.g., Tockner et al., 2006; Poole, 2010). As a consequence, key properties of habitat conditions (e.g., size, water depth, turbulence, shear stress, substrate composition, temperature, availability of cover, and food) that affect habitat use by the river biota change over time. For these reasons, it is more appropriate to consider geomorphic units and physical habitats as dynamic instead of static features, to study them through time, and to study the biota synchronously (in space and time) in order to link the physical to the biological environments and their dynamics.

As previously stated, the GUS units and sub-units correspond to the mesohabitat scale and small sub-units can also correspond to the microhabitat scale (i.e., river elements). This means that the spatial and temporal analyses of geomorphic units can be used for the survey and characterisation of physical habitats at meso- (units, sub-units) and microhabitat (substrates, flow types, etc.) scales, thus allowing links to be established with organisms even to the scale of individuals (Biggs et al., 2005). Moreover, the macro-unit analysis is also useful for the investigation of the broad fluvial landscape (riverine landscape ecology; e.g., Ward et al., 2002). These kinds of spatial analyses can incorporate landscape description metrics (e.g., patch form, connectivity, ecotones length, etc.) and diversity indices (e.g., Shannon, richness, dominance, etc.).

The analysis of relationships between geomorphic units (i.e., physical habitats) and biota through application of the GUS and its indices can provide a physical basis for biological surveys in terms of habitat heterogeneity, composition, and attributes at a scale that is geomorphologically meaningful. This is true for example for organisms like fishes and odonates, which given their size and habitat needs are sensitive to habitat types and diversity at the scale of geomorphic units (e.g., Golfieri et al., 2016; Wolter et al., 2016; for odonates and fishes, respectively).

Additionally, multiple, stage-dependent surveys through the GUS provide basic maps for the survey and characterisation of mesohabitats that can be used to (i) apply habitat simulation models for river habitat evaluation and environmental flow assessment (e.g., MesoHABSIM, Parasiewicz et al., 2013; Fig. 8); (ii) calculate the spatiotemporal variation of habitats through the calculation of habitat indices in relation to aquatic fauna (e.g., Vezza et al., 2014, 2015). In particular, the integration of mesoscale habitat models and GUS can define a more consistent modelling framework that can offer some advantages over the current methodology of physical habitat assessments. For instance, mesoscale habitat models integrated with GUS (i) can allow data to be collected at different flow conditions and a more appropriate scale for addressing environmental river management problems; (ii) may limit questions about the degree to which any particular reach (or cross section) represents a longer stretch of river of management interest; and (iii) may allow results to be upscaled to river sectors or entire catchments, which represent more relevant scales for the life-history strategies of many riverine species (Rinaldi et al., 2015a). A robust link between geomorphic classification frameworks and common ecohydraulic tools, such as habitat simulation models, is still in the early stage of development (Maddock et al., 2013), and the GUS can be considered one step for further research and applications in this interdisciplinary field.

River floodplains also show high spatial complexity owing to variability in their topography and spatial extent (e.g., Scown et al., 2015). This complexity is poorly addressed in applied river science given the greater interest of scientists and river managers in the most active zone of the river systems (i.e., channel, banks, and nearby riparian areas; Belletti et al., 2015a). As a consequence, most methods, procedures, and models developed for the survey and assessment of physical habitats in relation to biota focus on the river aquatic components (e.g., Hawkins et al., 1993; Raven et al., 1997; Vezza et al., 2015). Existing procedures that take account of the relationship between physical habitats and biota in the terrestrial zones of the river corridor generally address river-riparian vegetation interactions (e.g., Merritt et al., 2010; Egger et al., 2012; Gurnell et al., 2012; Garofano-Gomez et al., 2014; Gurnell et al., 2016b). Therefore, the fluvial terrestrial fauna and the terrestrial life stages of aquatic fauna have received relatively little attention (e.g., ground-dwelling terrestrial arthropods; Datry et al., 2014). There is a need to develop models of terrestrial habitats within the floodplain and the bankfull channel and combine them with ecological and biological models in order to obtain more complete and deeper assessments of river conditions at the ecosystem scale. The GUS maps and characterises terrestrial habitats (i.e., bankfull emergent and floodplain units), thus representing a valid supporting tool for terrestrial habitat modelling and biological surveys.

3.4. Limitations and future challenges

Despite the several applications that it supports, the GUS has some limitations that require further research and testing as well as greater synergy with ongoing technological advances.

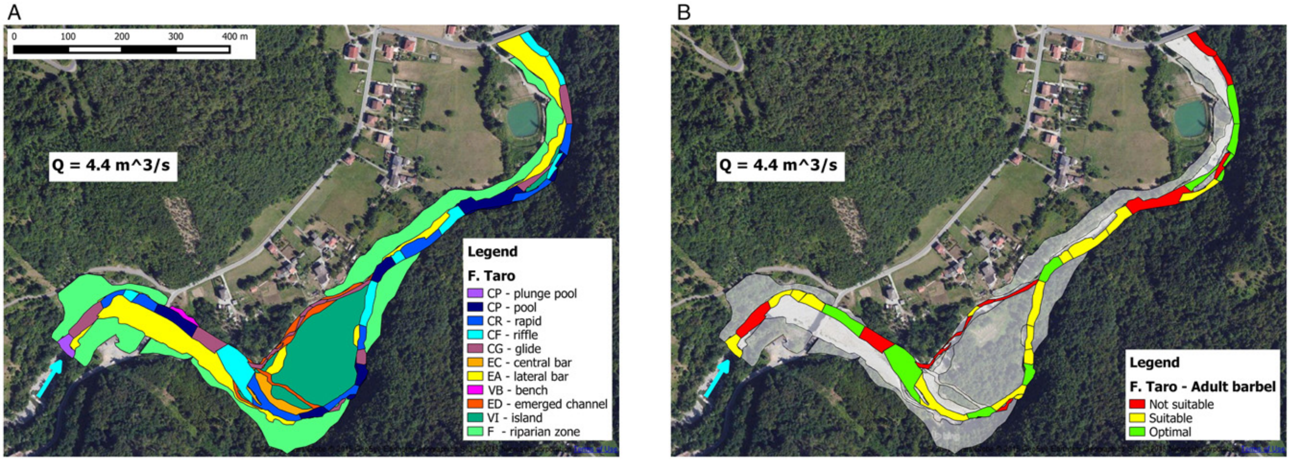


Fig. 8. Example of the application of the GUS for the survey and evaluation of mesohabitats for the Taro River (Parma, Italy). (A) Spatial distribution of geomorphic units (bankfull channel and floodplain units). (B) Evaluation of habitat suitability in terms of bed configuration units for adult barbel (*Barbus* sp.). Mesohabitats are classified in three categories: not suitable, suitable, and optimal. The flow rate at the time of the survey is also reported.
(Source: modified from Rinaldi et al. (2015d)).

Current limitations of the GUS can be summarized as follows:

- Application of the GUS requires quite a good level of expertise in fluvial geomorphology.
- Although the GUS is based on a clear, specific, and consolidated description of geomorphic units, identification of each unit type could be improved by developing, testing, and supplying threshold definitions.
- Although the method is recommended to be applied under low-flow conditions and the actual, morphologically based definition of units is not stage-dependant, the detection of river spatial features, especially in terms of habitats for biota, is influenced by water stage. Therefore, further tests are needed to compare unit recognition under different flow conditions.
- The GUS needs to be more extensively tested across a wide range of river types, mainly to improve its application as a tool for the analysis of physical habitats and thus to establish robust links with the biological components.
- To date, the GUS largely depends on field-based surveys.

In relation to technological advances, although field survey is a fundamental step in hydromorphological analysis, especially in some specific conditions (e.g., narrow and deep valleys, dense vegetation cover, small channels), recent and growing technological developments are leading to an increasing application of remote sensing for characterising river hydromorphology (Bizzi et al., 2016). Such technological advances have the potential to allow more objective, high-frequency assessments, and repeatable and large-scale monitoring of river systems (e.g., Casado et al., 2015; Bizzi et al., 2016). In this context, combining the science that underpins the GUS with remote/proximal sensing and GIS has enormous potential to provide a precise, robust, and repeatable delineation of geomorphic units and physical habitats within a well-framed geomorphological framework. The next step is to devise tools (e.g., algorithms, GIS procedures) to enable the translation of procedures incorporated in the GUS into automatic or semiautomatic mapping of geomorphic units for the extraction of map-derived indicators of river hydromorphology (e.g., Bizzi and Lerner, 2012; Casado et al., 2015; Roux et al., 2015; Demarchi et al., 2016).

4. Final remarks

The assessment of river hydromorphological conditions is now recognised as a fundamental step in the evaluation of river ecological conditions. Indeed, hydromorphological pressures are often one of the main causes of river system degradation, and existing biological tools are often rather insensitive to these pressures (Friberg, 2014; Rinaldi et al., 2015c), preventing the link between river hydromorphology and biota to be fully explored and understood.

The GUS has been developed to survey, classify, and characterise geomorphic units and thus physical habitats according to a well-defined spatially (and temporally) nested hierarchical framework for river hydromorphology (Gurnell et al., 2016a; Rinaldi et al., 2016a). This work is part of a wider effort to develop tools for river surveys that can be shared across Europe in the context of the Water Framework Directive. The GUS is a qualitative tool for the characterisation of reach hydromorphology at the scale of geomorphic units that supports an in-depth evaluation of river conditions. It is also a monitoring tool for assessing the impact of management actions on river hydromorphology at the scale of geomorphic units and the evolution of physical habitats through time. It thus constitutes a key tool to link morphological status at the reach scale with biological status at the site scale.

The GUS has been developed within a European context to cover a wide range of river conditions and types, but further improvements may be needed to cover specific situations or to include new findings and technological developments. In particular, the advances in remote and proximal sensing sensors and platforms (e.g., UAVs and new generation satellites) and techniques (e.g., application of information and communication technologies procedures) will aid the application of GUS to remote areas and at large scales.

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