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Regional hydromorphological characterization with continuous and automated remote sensing analysis based on VHR imagery and low-resolution LiDAR data

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Earth Surface Processes and Landforms

ABSTRACT: Recent developments in remote sensing (RS) technologies lead the way in characterizing river morphology at regional scales and inferring potential channel responses to human pressures. In this paper, a unique regional database of continuous hydromorphological variables (HyMo DB) based on areal and topographic data has been generated from RS analysis. Key riverscape units with specific geomorphic meaning have been automatically mapped for 1700 km^2 of river floodplains from simultaneous very-high-resolution (VHR) near-infrared aerial imagery and low-resolution LiDAR-derived products. A multi-level, geographical object-based architecture (GEOBIA) was employed to integrate both spectral and topographic information and generate a regional classifier able to automatically map heterogeneous fluvial patterns in different geographical and topographical contexts of the Piedmont Region (Italy).

This HyMo-generated DB offers a unique set of tools for hydromorphologists and can be exploited for different purposes. For the first time, topographic information can be exploited regionally per riverscape unit class, allowing for quantitative analysis of their regional spatial and statistical variability. In this manner, river types can be automatically characterized and classified using objective and repeatable hydromorphological variables. We discuss the potential of quantifying functional links between riverscape units and their driving processes, a valuable source of information to start assessing and highlighting the entity of potential channel adjustments at the regional scale to human pressures. The HyMo DB can also be integrated with historical, field-based information to better comprehend current fluvial changes at a local scale. In view of future RS acquisitions, the present approach will result in a suitable procedure for quantitative, objective and continuous monitoring of river evolutions over large scales. This type of hydromorphological characterization will allow regional trends and patterns to be highlighted through time and river management strategies to thus be implemented at both regional and local scales. Copyright © 2016 John Wiley & Sons, Ltd.

KEYWORDS: VHR and LiDAR data; object-based classification; regional scale; hydromorphological characterization

Introduction

Hydromorphological surveys of rivers have mostly been based on discontinuous field sampling along the river course (Raven *et al.*, 1997, 2002; Schmitt *et al.*, 2007; Rinaldi *et al.*, 2013; Gob *et al.*, 2014), often combined with visual interpretation of aerial images and manually derived measurements (Liébault *et al.*, 2013; Rinaldi *et al.*, 2013; Toone *et al.*, 2014). In recent years, remote sensing (RS) technologies have started to generate data of spatial resolution and coverage suitable for the development of semi-automated procedures to characterize important components of the hydromorphology of river systems at large scales, such as regionally. It has been recognized that RS data can provide novel insights into the investigation of fluvial forms and processes that cannot be achieved from classic field approaches (Marcus and Fonstad, 2007). In Europe, the process-based approach called river hierarchical framework (RHF) (Gurnell *et al.*, 2016) provides an open-ended framework to support river managers in assessing the hydromorphological character of EU rivers, as legally demanded by the Water

Framework Directive (WFD). It proposes a toolbox of several multi-scale indicators, which span several spatial and temporal scales, and allows a wide range of fluvial forms and processes to be characterized. Bizzi *et al.* (2016) have shown that, currently, depending on the scale of analysis, most RHF indicators can potentially be monitored through a wide range of RS sensors (e.g. multi-spectral, hyper-spectral, LiDAR or thermal) mounted on different platforms (e.g. satellite, airborne or unmanned aerial vehicles).

Despite this, most EU countries currently do not fully exploit the potentiality offered by RS technology for their hydromorphological surveys, even if the RS data are already available at regional and/or national scales (Bizzi *et al.*, 2016). We believe that the main limitation is the demanding efforts required to develop automated and semi-automated RS-based methodologies able to extract meaningful indicators at large scales (Newson and Large, 2006).

In 2007, Marcus and Fonstad (2007) advocated moving beyond the proof-of-concept studies at the local scale and creating initiatives that support river mapping at watershed extents. In their paper, they showed the potentials of optically based, spatially continuous, sub-meter-resolution data for the mapping of several river parameters at the watershed extent (Marcus and Fonstad, 2007). Similarly, several other researchers have mapped specific variables continuously at basin extents. Airborne digital imagery has been used for automated catchment-scale mapping of the grain size in fluvial environments by Carbonneau *et al.*, 2004, 2005, and for watershed-extent maps of stream power by Jordan and Fonstad (2005). More recently, Bizzi and Lerner (2013) calculated channel gradient and stream power using digital terrain models (DTM). Handcock *et al.* (2012) showed how thermal infrared remote sensing can be used to monitor the spatial patterns of water temperature in streams and rivers at multiple scales, from fine-scale hydrologic features to regional floodplains and river sections. Alber and Piégay (2011) developed a methodology to analyze the river pattern continuously at the regional scale (based on DTM and for heterogeneous fluvial forms), which was then applied in Notebaert and Piégay (2013) to calculate the floodplain width at the regional scale. These innovative studies, however, mapped specific variables and/or channel hydromorphological components. There is still no exhaustive framework to map the extent and topography of key riverscape units to provide a full characterization of the distribution of channel and floodplain forms along the entire river system under analysis.

Indeed, an essential aspect when characterizing the hydromorphology of a river is the ability to identify channel boundaries and associated riverscape units (e.g. flow channel, bare sediments, floodplain, sparsely vegetated units, densely vegetated units, etc.) composing the valley bottom. These units are process signatures, i.e. through forms and distribution, they indicate which fluvial processes are occurring and where. For instance, the active channel (AC) is defined in the literature as the low-flow channel plus adjacent exposed sediment bar surfaces between established edges of perennial, terrestrial vegetation, which are generally subjected to erosion or deposition (Marcus *et al.*, 2012; Belletti *et al.*, 2013). Vegetation encroachment, which occurs on exposed sediment bars, from sparsely to densely vegetated patches along the margins of the channel or islands, has a key role in the evolution of the active channel pattern (Gurnell *et al.*, 2001). Mapping riverscape units objectively over time is then of pivotal importance to understand the morphodynamics of a river system, as described in established hydromorphological survey methods (Brierley and Fryirs, 2005).

However, few studies have attempted to map these key units on large scales in an automated/semi-automated and objective manner. For instance, Piégay *et al.* (2009) performed a census of the braided rivers in the French Alps by visually mapping the braided reaches on the available aerial photos. Bertrand *et al.* (2013) mapped riverscape units and channel types on RGB orthophotos for the Drôme catchment (France), using an object-based approach (GEOBIA). Michez *et al.* (2013, 2014) used LiDAR and photogrammetric digital surface models for the characterization of the riparian zones from local to regional scales in Wallonia (Belgium). Stout and Belmont (2014) developed a semi-automated selection of fluvial terraces and floodplain features from LiDAR data. Belletti *et al.* (2014) manually digitized channel boundaries and associated riverscape units on available orthophotos with the aim of analyzing historical changes in channel morphology for a set of reaches.

These previous experiences inspired the current work. However, none of them fully characterized riverscape units, including in-channel and floodplain features, through an automated RS procedure. Stout and Belmont (2014) and Michez *et al.* (2013, 2014) focused primarily on floodplain features and did not fully characterize in-channel riverscape units, while neither Piégay *et al.* (2009), Bertrand *et al.* (2013) nor Belletti *et al.* (2014) developed a real automated RS analysis or integrated with LiDAR information. In fact, in these cases, the common limitation in automating such procedures at a regional scale was the lack of simultaneity between spectral and LiDAR information at sufficient spatial resolution and coverage, an important data requirement as raised in Bizzi *et al.* (2016).

In a recent study, we showed how simultaneous spatial and topographic information can be exploited to automatically map riverscape units (Demarchi *et al.*, 2016). A GEOBIA classification methodology was developed on very-high-resolution (VHR) near-infrared aerial imagery (0.4 m) and low-resolution LiDAR-derived products for 45 km of the Orco River (Italy). The results showed notable potentials and robustness in mapping the key riverscape units, therefore opening novel perspectives in terms of automating the classification procedure for regional datasets.

In the present paper this new step was explored, applying our methodology at the regional scale, with the aim of generating layers of information of key riverscape units that are suitable to support a regional hydromorphological characterization and detect potential human pressures. In the first part of the paper, we integrate the spectral and topographic information (VHR imagery and low-resolution LiDAR-derived products) of the main river network of the Piedmont Region, Italy (approximately 1700 km^2) within a multi-level GEOBIA to map the key riverscape units. In the second part of the paper, we demonstrate the utility of the generated RS mapping to support a quantitative characterization of fluvial forms across the region. For this purpose, a database of hydromorphological features was created from the RS classification results, adopting the spatial disaggregation approach of Alber and Piégay (2011). This type of hydromorphological database (HyMo DB) describes with continuous information the extent and topographic variability of the riverscape units composing the natural fluvial corridor of 1700 km^2 of floodplains in the Piedmont Region, for a cumulative river length of 1200 km. This type of systematized hydromorphological information did not exist before and can be a way to quantitatively implement and realize the riverscape concept of Carbonneau *et al.* (2012), in which the spatial distribution of geomorphic variables is essential throughout entire river systems. We therefore demonstrate the utility of the HyMo DB to produce quantitative, statistical and objective analyses, such as Hubert segmentation (Hubert *et al.*, 1989) and Hierarchical clustering (Ward, 1963), in support of river-type classification and characterization at the regional scale (Kondolf *et al.*, 2003). Furthermore, we discuss quantifying functional links between riverscape units and their drivers by analyzing topographic features and channel planforms per river type. We then show the potential to integrate the HyMo DB with local historical information to support more detailed interpretations of historical and on-going channel adjustment processes at the local scale. Finally, we conclude by discussing future developments of the method in view of increasing RS data availability and the potential of such a framework to question established ideas in fluvial geomorphology.

Study area

The Piedmont Region is located in the northwest of Italy, covering an area of 25 387 km^2. The Po River, the longest Italian river (total length of 652 km, crossing four Italian regions), has its source in the Piedmont Region. All the main regional river networks drain into it. Two primary mountain chains shape the orography of the region: in the south, the northern Apennine, and in the west and north sides, the Alps. The Po River flows into the Pianura Padana floodplain from west to east. The Alps are higher in altitude compared with the Apennine (4000 m.a.s.l., compared with 2000 m.a.s.l.), and the lithology is, unlike the Northern Apennines, mainly composed of metamorphic rocks (e.g. gneiss, schist and serpentines) that are mainly formed by sedimentary rocks (e.g. sandstone, mudstone and marl). The climate is temperate, and precipitation is concentrated primarily in autumn and spring, although in summer, short and intense storms can occur in the mountain areas. Snowmelt is particularly important in spring and early summer flows of the Alpine rivers.

Most of the upstream and medium valley rivers of the region are dynamic gravel-bed rivers, with high bedloads supplied from the Alps or the Apennine, which generate wide

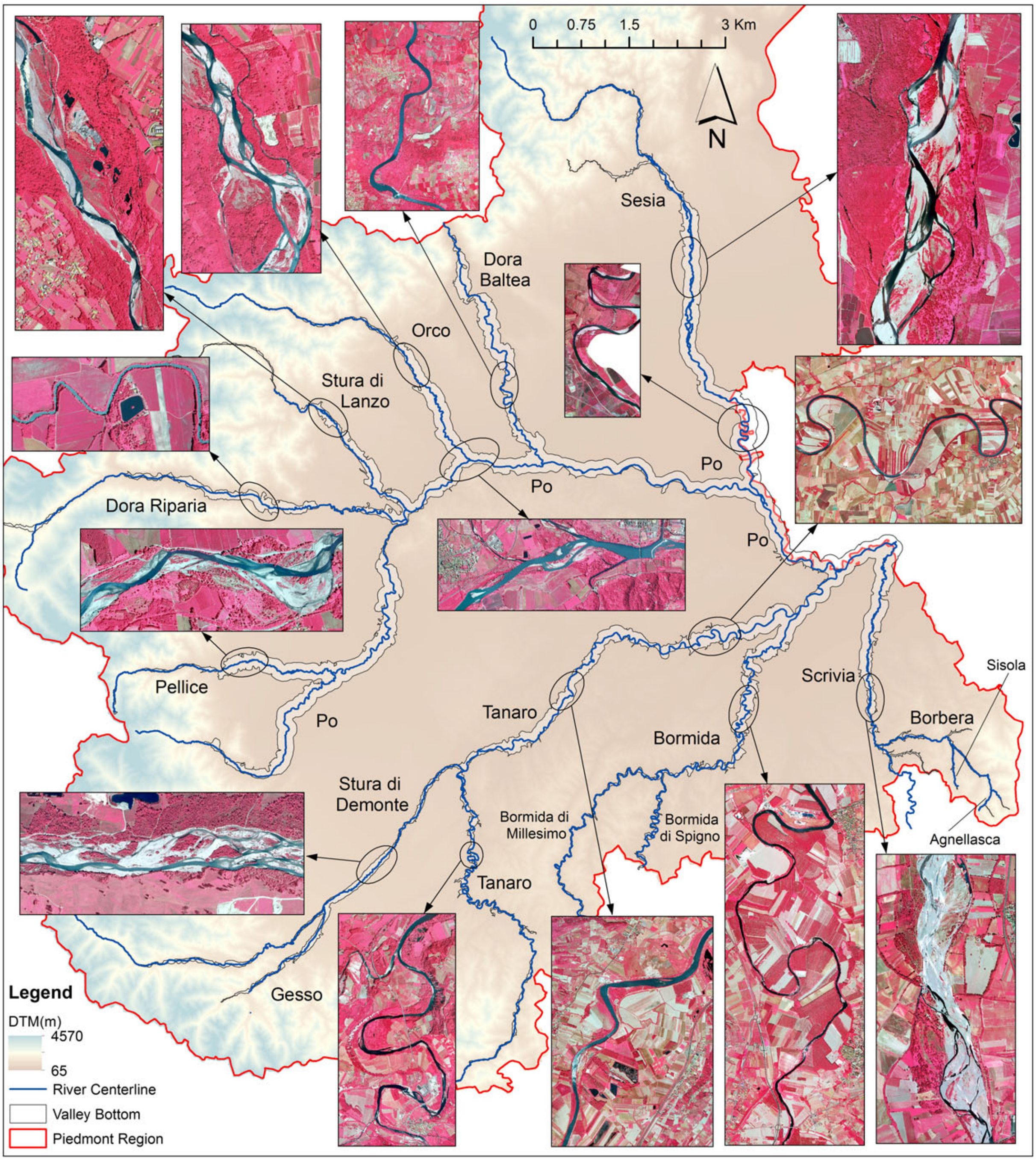

Figure 1. River network selected within the Piedmont Region. Near-infrared orthophotos (false color composite) show the different existing river patterns. [Colour figure can be viewed at wileyonlinelibrary.com]

in-channel bars. If human pressures do not significantly impact them, they develop mostly braided and wandering patterns (Figure 1). Braided planforms evolve into sinuous and meandering types when flowing downstream, connected with a decrease in slope and fining and sorting of the bedload. The spatial distribution of these transitions is very heterogeneous across the region, and it is driven by local lithology, geology, current and past climate forcing and the legacy of human pressures.

Methodology

Remote sensing and GIS data used for analysis

During the years 2009/2010, the Piedmont Region (Italy) commissioned a flight acquisition campaign to cover the entire region (approximately 25 000 km^2) with simultaneous 40 cm near-infrared orthophotos and topographic LiDAR (at 0.4 points/m^2). Because of its nature, the LiDAR sensor did not record any water surface elevation data. The point clouds were processed by the producing company to deliver a DTM interpolated at 5 m ground resolution. Therefore, the water surface elevation was generated by interpolation of available recorded points surrounding the water surface. Depending on the density of points, the elevation accuracy of the dataset varies on average between 30–50 cm. VHR and LiDAR imageries were projected into the Lambert azimuthal equal-area projection (LAEA) to fulfill the INSPIRE Directive requirements (EC, 2007).

The 'Fluvial Corridor' toolbox proposed in Roux *et al.* (2014) was adopted for the delineation of the Valley Bottom (VB), defined as the modern alluvial floodplain by Alber and Piégay (2011). In this work, the toolbox was applied on the 18 river centerlines selected within the regional river network (see Figure 1), which corresponded to a total of 262 image tiles (of approximately 6.7 × 5.7 km^2 each). Due to the RS data resolution, we analyzed river channels wider than at least 5 times the DTM resolution, i.e. larger than 25 m, and where riparian vegetation was not excessively overhanging the channel to be able to extract its hydromorphological features. Therefore, headwaters and minor tributaries were neglected. After selection, we analyzed a total of 1200 km of river lengths in the region, subdivided into 18 rivers: they represent the main hydrographic network of the Piedmont Region (see Figure 1).

The 'Fluvial Corridor' toolbox was also employed for calculation of the Detrended Digital Terrain Model (DDTM) by using the river centerlines and the DTM as inputs. The DDTM represents the height of each floodplain pixel with respect to the river centerline, and if well exploited, it can be essential in distinguishing different geomorphic features (Demarchi *et al.*, 2016). For each of the 262 image tiles, the normalized difference vegetation index (NDVI) was calculated using the Red and Near-infrared spectral bands of the VHR imageries, while the Slope was calculated by applying the Zevenbergen–Thorne method (Zevenbergen and Thorne, 1987) on the DTM images.

Definition of riverscape units

An exhaustive characterization of riverscape units includes all landscape elements directly affected by fluvial processes, including the FloodPlain (FP) and the morphological active channel (AC). The AC, as briefly discussed in the introduction, is composed of the low-flow water channel (WC), unvegetated sediment bars (USs) and sparsely vegetated units (SVs). SVs are important indicators of ongoing vegetation encroachment, a process that occurs on sediment bars and has a key role in the evolution of active channel planform and associated islands (Gurnell *et al.*, 2001). The SVs can be further subdivided into Riparian (RSVs) and Island variants (SVIs) if surrounded by the WC and/or USs. Within the FP, it is possible to identify riparian densely vegetated units (RDVs) and densely vegetated islands (DVIs) from other floodplain units (OFUs). SVIs and DVIs are found within the AC boundaries and therefore are entirely surrounded by the WC and/or USs. Alternately, RSVs and RDVs are vegetation units adjacent to the AC but not entirely surrounded by it. The WC, USs, SVs and DVIs form the total active channel (TAC) (Toone *et al.*, 2014).

The major challenge of mapping riverscape units automatically for the entire region using RS data lies in distinguishing some of the AC classes (e.g. USs and SVs) from those landscape features that can be found within the floodplain (the FP class) and that have similar spectral characteristics. DVIs need to be differentiated from the densely vegetated areas found within the floodplain and belonging to the OFU class. At the same time, SVIs present very similar characteristics to crop fields found within the floodplain and characterized by an intermediate level of vegetation growth. Furthermore, USs are spectrally comparable with crop fields left fallow due to crop rotation practices and to some mining sites that can be found in the floodplain. Similarly, gravel rural roads or urban settlements are found within the floodplain and belong to the FP class. Parsing the spectral similarity between urban areas and bare soil fields is a huge challenge, even for RS data operating at high spatial and spectral resolution (e.g. hyperspectral data) (Demarchi *et al.*, 2012; Weng, 2012).

Object-based classification of riverscape units at the regional scale

The peculiarity of geographic, object-based image analysis (GEOBIA) is the grouping of connected pixels with similar characteristics into meaningful image objects, akin to the way humans conceptually organize the landscape to comprehend it (Hay and Castilla, 2008). As opposed to pixel-based approaches, the advantage of GEOBIA is the integration of a broad range of different object features into the analysis process. Topological relationships with neighbor objects, statistical summaries of spectral or textural values, and shape characteristics can all be calculated and employed in the classification procedure, potentially improving the accuracy in advanced classification problems (Benz *et al.*, 2004), such as the one approached in this work: riverscape unit classification. Furthermore, GEOBIA allows coupling the spectral and topographic information and therefore enhancing the limited spectral resolution of VHR imagery (only three spectral bands).

The riverscape unit segmentation and classification methodology was developed in Demarchi *et al.* (2016) for a 45 km section of the Orco River (Italy). In this study, the same procedure was implemented within eCognition Developer 9 ® software and automatized for the 262 image tiles analyzed. The segmentation stage splits an image into unclassified objects that form the basis of the classification process. In Demarchi *et al.* (2016), this was done by implementing a hierarchical two-level segmentation based on the two sources of RS data available to generate objects that are as closely related to real-world objects as possible. The first level of the hierarchical segmentation was produced using the Slope layer alone (Level 1, Figure 2), while the second, finer sub-level segmentation was produced using the four spectral layers available (Level 2, Figure 2): Green, Red, Near-infrared and NDVI. The two-level segmentation process proved to be effective in facilitating the challenging task of distinguishing the main

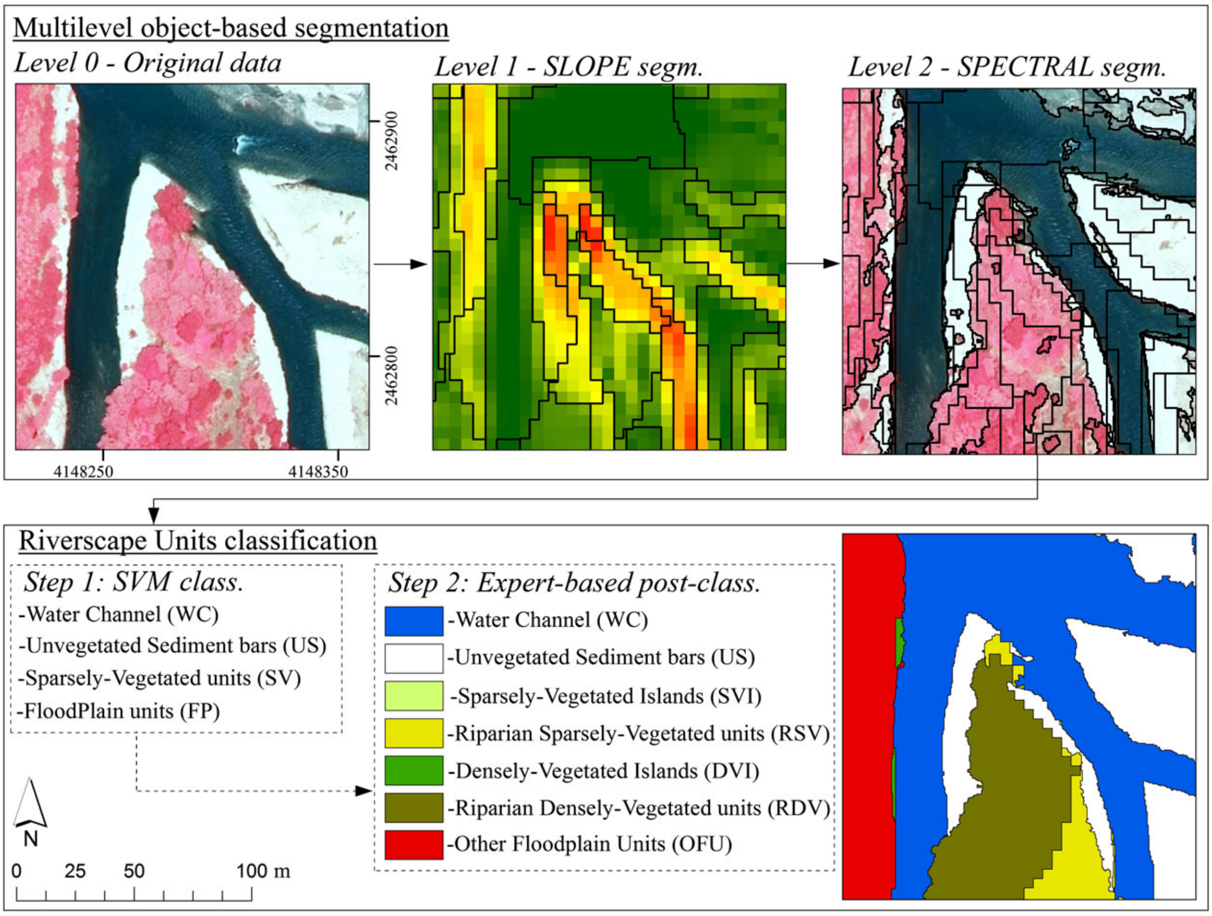

Figure 2. Object-based classification framework for mapping riverscape units at the regional scale from Demarchi *et al.* (2016). [Colour figure can be viewed at wileyonlinelibrary.com]

Table I. List of Hymo indicators calculated for different purposes at the regional level based on the RS classification results

Acronym	Description	Scale and calculation	Use
WC_area	Water Channel area	DGO level: zonal stat.	
US_area	Area of Unvegetated Sediment bars	DGO level: zonal stat.	
US_hgt	Height of Unvegetated Sediment bars	DGO level: DDTM zonal stat.	
SVI_area	Area of Sparsely-Vegetated Islands	DGO level: zonal stat.	
SVI_hgt	Height of Sparsely-Vegetated Islands	DGO level: DDTM zonal stat.	
RSV_area	Area of Riparian Sparsely-Vegetated units	DGO level: zonal stat.	
RSV_hgt	Height of Riparian Sparsely-Vegetated units	DGO level: DDTM zonal stat.	
DVI_area	Area of Densely-Vegetated Islands	DGO level: zonal stat.	
DVI_hgt	Height of Densely-Vegetated Islands	DGO level: DDTM zonal stat.	Hubert segmentation
RDV_area	Area of Riparian Densely-Vegetated units	DGO level: zonal stat.	
RDV_hgt	Height of Riparian Densely-Vegetated units	DGO level: DDTM zonal stat.	
OFU_area	Area of Other Floodplain Units	DGO level: zonal stat.	
OFU_hgt	Height of Other Floodplain Units	DGO level: DDTM zonal stat.	
AC_area	Active Channel area	DGO level: WC_area + US_area + SVI_area + RSV_area	
TAC_area	Total Active Channel area	DGO level: AC_Area + DVI_area	
RC_area	Riparian Corridor area	DGO level: TAC_Area + RDV_area	
VB_area	Valley Bottom area	DGO level: RC_Area + OFU_area	
Slope_DGO	Water surface Slope	DGO level	
WC_AC	Percentage of WC_area with respect to the AC area	On the Hubert segments: mean(WC_area/AC_area)	
DVI_TAC	Percentage of DVI_area with respect to the TAC area	On the Hubert segments: mean(DVI_area/TAC_area)	
Slope	Averaged Water surface Slope	On the Hubert segments: mean(Slope_DGO)	Hierarchical Clustering
Sinuosity	Water Channel Sinuosity	Mean on the Hubert segments	
AC_norm	AC width normalized by Basin area	On the Hubert segments: mean((AC_area/100)/Basin_area)	
Conf	Confinement	On the Hubert segments: mean(AC_area/VB_area)	
AC_W	AC Width	On the Hubert segments: mean(AC_area/100)	River types understanding
FP_hgt	Floodplain height	On the Hubert segments: mean(OFU_hgt)- mean(US_hgt)	

land-cover classes found in the active part of the channel (i.e. the WC, USs and SVs from Table I) from areas of the FP class characterized by very similar spectral characteristics (Demarchi *et al.*, 2016). Implementing the slope and spectral segmentations at the regional scale required approximately 80 min per tile, for a total of approximately 350 h of processing time, using a CPU running at 2.3 GHz and 32 GB of RAM.

The classification stage was approached in two steps due to the strong spectral and topographic similarities between some of the classes, as suggested in Demarchi *et al.* (2016). In the first step (Step 1 of Figure 2), a regional object-based classifier was built with the aim of automatically mapping the main riverscape units (the WC, USs, SVs and FP) and therefore delineating the AC boundaries (the WC, USs and SVs) from the FloodPlain class (FP). The best classification results obtained in Demarchi *et al.* (2016) for the Orco River were produced when classifying the Spectral and DDTM features with the support vector machine (SVM) classifier, resulting in a K accuracy of 0.91. These results have been manually corrected of eventual errors and used as training samples to feed a new regional classifier based on a much higher number of samples (approximately 190 000 labeled objects), and they are therefore expected to be able to handle the much higher class variability that can be found when implementing the classification methodology at the regional scale. Spectral and DDTM features were therefore used as object-based input features to train the new SVM regional classifier.

For the assessment of the SVM at the regional scale, validation objects were manually classified based on visual expert-based interpretation of the VHR imagery. The validation sampling collection was particularly time consuming but resulted in a spatially distributed dataset along the entire region, covering an area of approximately 100 km^2 (approximately 6% of the total classification area).

The second step of the riverscape unit classification (Step 2 of Figure 2) consisted of the identification of vegetation classes at a higher level of detail. This step was implemented using expert, object-based rule-sets defined by specific criteria according to each riverscape unit class. For example, SV objects were re-classified as RSVs or as SVIs if their relative border to the FP class was, respectively, above or below 0.1. This and other rule-sets are fully detailed in Demarchi *et al.* (2016) and were applied regionally in this paper.

Regional hydromorphological database (HyMo DB) for river-type classification and characterization

A regional HyMo DB was created using the regional RS classification of riverscape units. The VB shapefile was disaggregated into spatial units (called Disaggregated Geographical Objects (DGO); see Figure 3(ii)) following the GIS methodological framework described in Alber and Piégay (2011). DGOs are relatively high-resolution spatial units (100 m each) that allow hydromorphological features to be characterized continuously along river networks. In this study, the DGO approach was selected because it proved to have great potential for supporting the large-scale hydromorphological characterization of fluvial systems. For each DGO, we extracted several hydromorphological indicators (Table I and Figure 3(iii)). The areal extent and the height of each riverscape unit class obtained from the regional RS results were calculated for each DGO with GIS zonal statistics procedures, also making use of the DDTM layer for the height and therefore representing the relative elevation of each of the classes compared with the channel elevation. The areal extent and height are particularly important indicators because they are linked to specific hydromorphological processes taking place in the river system, such as, for example, confinement, narrowing, widening, incision or aggradation. The AC area (AC_area, Table I) was calculated by summing the area of the WC, US, SVI and RSV classes. The total active channel (TAC) area (TAC_area, Table I) was calculated by adding the DVI area (DVI_area, Table I) to the AC_area, while the same was done for the riparian corridor (RC) area (RC_area, Table I) by adding the RDV area (RDV_area, Table I) to the TAC_area. The VB area (RC_area, Table I) is the total area covering each DGO unit. Finally, the water surface slope (Slope_DGO, Table I) was calculated every DGO of 100 m using averaged values of a resampled DTM at 25 m to avoid oversinuosity issues, following the approach of Biron *et al.* (2013).

We intended to segment rivers into reaches of a few kilometers or less, suitable for classification into different functional types. With this purpose, we localized homogenous stretches using the statistical Hubert segmentation analysis (Hubert *et al.*, 1989) on the four main hydromorphological drivers (Figure 3(iv)): Valley Bottom, Riparian Corridor, Active Channel and Slope (VB_area, RC_area, AC_area and Slope_DGO of Table I, respectively). These hydromorphological variables affect channel processes in different ways. Valley Bottom determines the available room for the lateral channel shifting. The presence or absence of a Riparian Corridor controls the bank resistance to erosion and, consequently, the channel width and shifting, creating specific feedback mechanisms between sediment fluxes and hydraulic efficiency related to vegetation dynamics of encroachment and scour (Bertoldi *et al.*, 2011). Active Channel width is an important hydromorphological feature varying among river types and is known to be sensitive to the alteration of morphological processes, notably in such mountain regions (Alber and Piégay, 2011; Bertrand *et al.*, 2013). For example, a decrease in sediment supply often triggers vegetation colonization and associated channel narrowing in many northern Italian rivers (Surian *et al.*, 2009). Finally, Slope is a main driver of the channel energy and thus of the ability of the river to produce channel adjustments (Jain *et al.*, 2006; Bizzi and Lerner, 2013).

In a second step, for each of the Hubert segments resulting from the intersection of the four segmentations, we calculated averaged information at the segment level. A Hierarchical Clustering analysis (Ward, 1963) was performed on the Hubert segments based on six hydromorphologically meaningful indicators (Figure 3(vi) and 3(vii)): the percentage of Water Channel within the AC (WC_AC), percentage of DVI within the TAC (DVI_TAC), Slope, Sinuosity, AC normalized by the basin area (AC_norm), and Confinement (Conf) (Table I), following Bertrand *et al.* (2013). These parameters allow the main planforms that characterize river types to be described, for instance, WC_AC is important for distinguishing braided versus wandering river types, while DVI_TAC is important for identifying river types with islands. In particular, Confinement is calculated as the ratio between AC_area and VB_area. AC has been normalized by the basin area to detect variations of channel widths affected by channel processes removing the influence of the basin size (Piégay *et al.*, 2009). Furthermore, the Sinuosity was calculated using the 'Fluvial Corridor' (Roux *et al.*, 2014) and averaged within each Hubert segment. Hierarchical Clustering allows specific river types, defined by the variability combination of the six hydromorphological indicators selected, to be identified, and therefore it can be used to describe specific hydromorphological patterns (Figure 3(viii)).

Once the river-type classification was finalized, statistical relationships were explored between different indicators within the same river type with the aim of characterizing river types at a higher level of hydromorphological process understanding. For this purpose, we enriched the planforms information with

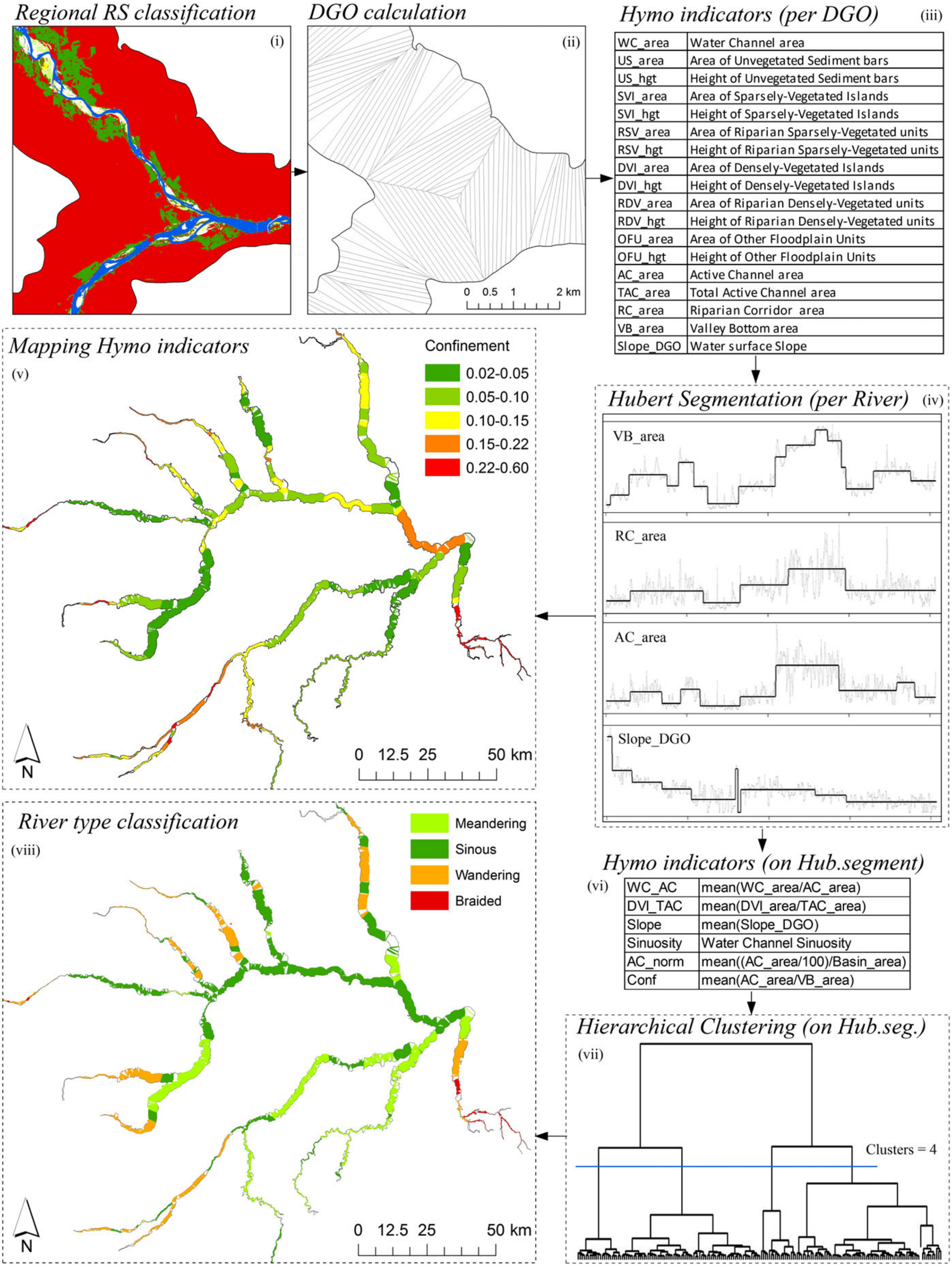

Figure 3. Flowchart of the regional Hymo database preparation and analysis. [Colour figure can be viewed at wileyonlinelibrary.com]

topographic information and investigated whether or not different river types have distinctive relationships between the basin area and AC width (AC_W, Table I) or Floodplain height (FP_hgt, Table I). The floodplain height was calculated as the difference between the mean floodplain (OFU_hgt50, Table I) and mean sediment bar (US_hgt50, Table I) heights above the low flow channel.

Table II. PA and UA obtained from the Step 1 classification results and after the manual correction of errors

	Step1: class. Results			After manual correct.	
	PA	**UA**		**PA**	**UA**
WC	93.42	91.14	**WC**	93.42	91.14
US	83.35	76.92	**US**	86.26	86.15
SV	**62.68**	**52.06**	**SV**	**81.66**	**84.45**
FP	97.43	98.38	**FP**	98.74	98.75

The HyMo DB was also integrated with local available field-based historical information to support more detailed interpretation of on-going channel adjustment processes at the local scale. For this purpose, we analyzed all DGOs of 100 m, for a section of 30 km of the Orco River, and combined the new hydromorphological variables calculated from RS data with existing historical field-based data of Active Channel areas. Historical areas occupied by the Active Channel were previously manually mapped for the years 1954, 1962, 1975, 1991, 2003 and 2009. For each year, the Active Channel area was averaged every DGO of 100 m, providing spatially and temporally distributed information and allowing widening and narrowing processes to be explored. Historical field-based cross-sections were also available for the years 1975 and 2003. The difference of the interpolated averaged altitude for each cross-section series was calculated, providing an indication of the degree of riverbed incision and aggradation between these two dates.

Results

Regional riverscape unit classification assessment

The results of the Step 1 riverscape unit classification at the regional scale (Figure 2), using the SVM classifier based on the Spectral and DDTM features, produced a K accuracy of 0.72 (Table II). The Producer's Accuracy (PA) is very high for the FP and WC classes (97.4 and 93.4, respectively), worse for the US class (83.3) and relatively low for the SV class (62.7). The user's accuracy (UA) shows a similar trend as well, with the lowest value recorded for the SV class (52.1). The low UA for the SV class corresponds to a total Commission Error (CE) of 47.9% (Table III), indicating that 47.9% of the pixels classified as SV class should instead have been classified as another class: in this case, 47.2% of them as FP (Table III). In other words, a significant amount of floodplain objects were classified as sparse vegetation, underlying the difficulty of the classifier in automatically distinguishing these classes at some locations of the region. The total Omission Error (OE) of the SV class is high as well: 37.3% of the validation SV pixels were not classified as SV, but 29% were as FP class (Table III). CE and OE are also relatively high for the US class (23.1% and 16.7, respectively; see Table III), which was mostly misclassified with the FP class.

A visual assessment was performed to understand the nature of these errors and their localization within the region. Figure 4 shows a few examples of the visual assessment for different river types. We noticed that most of the errors occur for lowland river reaches, e.g. for the Po River at the junction with the Dora Baltea River (Step 1 results of Figure 4(iii)). This might be because the classifier was trained using the classification results of the Orco River, an upland river, with topographic values that might differ from the lowland reaches where the CE and OE for these two classes were detected. For other rivers, the classifier worked well. For example, the meandering pattern of the Tanaro River was classified with almost no errors, although numerous bare soil fields were found within the floodplain (see Step 1 of Figure 4 (iv)). This shows the remarkable potential of the methodology to be flexible to different geographical and topographical contexts and, eventually, to different case studies.

The large localized errors between the USs, the SVs and the FP classes were manually corrected before starting the Step 2 expert-based post-classification. The GEOBIA segmentation creates meaningful objects in terms of topography and spectral signatures, and for this reason, an expert-based clean-up of the results is feasible and to be encouraged to remove local misclassification, which is unavoidable with an automated procedure at the regional scale. It took approximately 4 hours work to correct these errors over the entire region. This resulted in a significant improvement of the PA and UA of the SV class (81.66 and 84.45, respectively; see Table II) and of the US class (86.26 and 86.15, respectively; see Table II). The CE of the SV class was reduced from 47.94% to 15.55% for the SV class (Table IV) and from 23.08% to 13.85% for the US class (Table IV). These figures emphasize the quality of the validation dataset, visually collected with a spatial distribution uniformly spread across the entire region and therefore sensible to this type of change.

Table III. CE and OE obtained for the Step 1 classification results

	Commission errors (CE)						Omission errors (OE)				
	Total	**WC**	**US**	**SV**	**FP**		**Total**	**WC**	**US**	**SV**	**FP**
WC	***8.86***	--	0.92	0.55	7.39	**WC**	***6.58***	--	0.20	0.05	6.33
US	***23.08***	0.24	--	4.74	18.09	**US**	***16.65***	1.25	--	0.60	14.79
SV	***47.94***	0.08	0.71	--	47.15	**SV**	***37.32***	1.05	7.27	--	29.00
FP	***1.62***	0.31	0.55	0.76	--	**FP**	***2.57***	0.37	0.72	1.48	--

Table IV. CE and OE obtained after the manual correction of errors

	Commission errors (CE)						Omission errors (OE)				
	Total	**WC**	**US**	**SV**	**FP**		**Total**	**WC**	**US**	**SV**	**FP**
WC	***8.86***	--	0.92	0.55	7.39	**WC**	***6.58***	--	0.20	0.05	6.33
US	***13.85***	0.24	--	4.68	8.93	**US**	***13.74***	1.14	--	0.55	12.05
SV	***15.55***	0.07	0.64	--	14.84	**SV**	***18.34***	0.77	5.30	--	12.27
FP	***1.25***	0.31	0.49	0.44	--	**FP**	***1.26***	0.37	0.37	0.52	--

After the manual correction of the classification errors, Step 2 (Figure 2) consisted in applying expert, object-based rule-sets developed in Demarchi *et al.*, 2016, to map vegetation classes at a higher level of detail. Without the need to modify thresholds or other parameters, the rule-sets worked well for the entire region, underlying the robustness of the GEOBIA methodology for large-scale applications. Nevertheless, a few small errors were still manually corrected at a few locations. Figure 4 shows

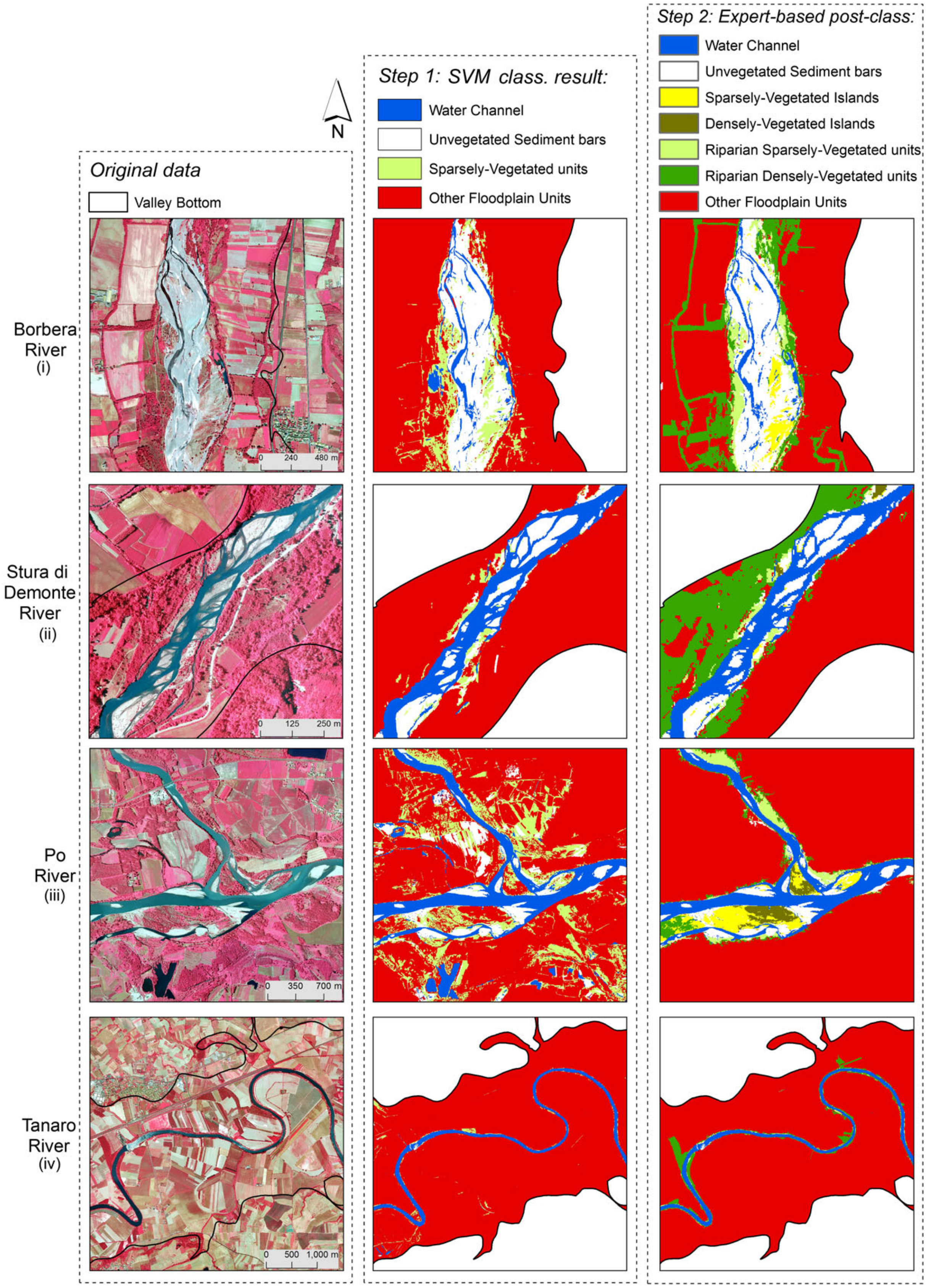

Figure 4. Examples of the classification results obtained with the Step 1 SVM classification and the improvement obtained after the Step 2 expert-based post-classification for different river patterns (also see Figure 2). [Colour figure can be viewed at wileyonlinelibrary.com]

some examples obtained for different rivers. Applying these rule-sets allowed hydromorphological landforms to be automatically distinguished at a higher level of detail, for example, the high amount of US features or the spatial structure of the Riparian Corridor, evidenced by the RDV class on the Borbera and Sesia reach (Figure 4). Alternatively, the total absence of RDV, SV and US classes for the meandering section of the Tanaro River, where the AC is mostly composed of Water Channel alone (Figure 4).

RS classification results are also shown in Figure 5, to give an example of the different landforms that are mapped automatically at the regional scale with RS data and to strengthen the robustness of the proposed methodology to map riverscape units at large scales and in different geographical and topographical contexts.

Definition of regionally meaningful hydromorphological reaches

From the 1700 km^2 of riverscape unit mapping obtained from the RS classification results, a HyMo DB was generated. The database is one of the first attempts to build virtually

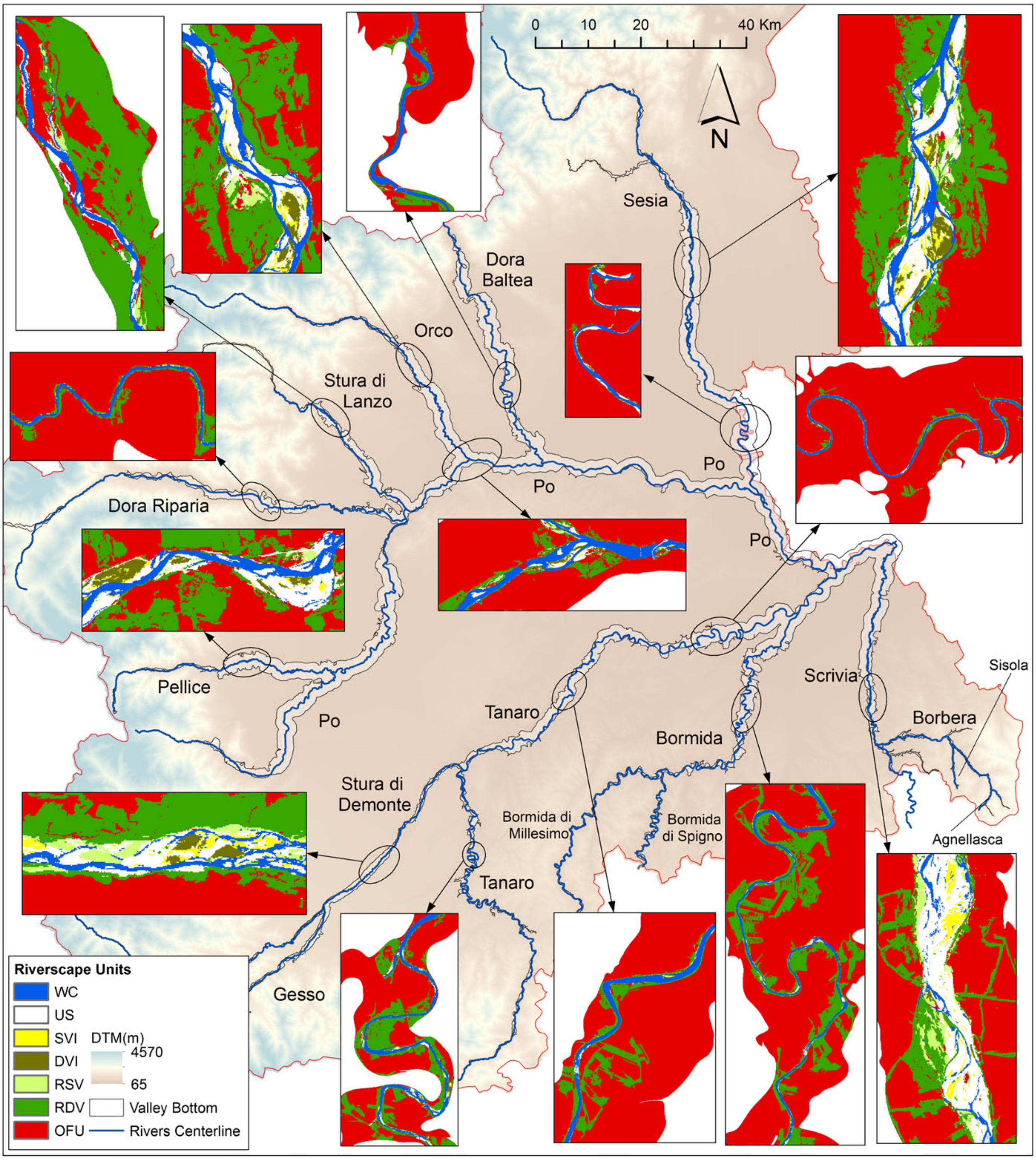

Figure 5. Example maps of riverscape units for a set of reaches at the regional scale. Orthophotos of individual reaches are shown in Figure 1. Riverscape class codes are defined in Figure 2. [Colour figure can be viewed at wileyonlinelibrary.com]

continuous information on hydromorphological river features at a regional level, providing information on a number of hydromorphological variables (see Table I, Section 3.4) for every DGO at 100 m, resulting in a total of approximately 12 000 units to be analyzed. It describes a wide variety of river types, from major river systems in the region – such as the Po and Tanaro Rivers, which flow for more than 150 km within the study area – to high-energy upland tributaries, such as the Borbera or the Scrivia Rivers.

To identify homogenous river reaches in hydromorphological terms, every river was individually segmented, adopting the Hubert test on four parameters (VB, RC, AC, Slope). Figure 6 shows an example of the segmentation chart obtained for the Stura di Demonte River. Light-grey lines represent the data at DGO level (every 100 m) and the black step lines represent the average values, calculated by the Hubert segmentation, for each generated segment. The final segmentation is obtained by integrating these four layers; basically, a new reach is created each time a rupture occurs in one of the four parameters.

For the purpose of river-type classification and characterization, we then selected among these reaches only those longer than 1 km to remove local scale phenomena and concentrate the analysis on river stretches sufficiently long and homogenous with the aim of properly describing the main attributes of a river type. This resulted in a total of 183 river segments for the entire regional database, with segment lengths varying from 1 km to a maximum of 40 km, the majority of which fell in the range 5–15 km.

Boxplots in Figure 7 show the distribution of average values along the Hubert segment generated for WC_AC, Slope, AC_norm and Conf (Table I). Major rivers (e.g. Po, Tanaro, and Sesia) and minor tributaries (e.g. Scrivia and Barbera) together provide a wide range of river channels to be analyzed. Major rivers show a wider variance, because the HyMo DB describes the river longitudinal development for a longer distance. Slope varies from >0.01 (e.g. streams such as Agnellasca, Sisola, Gesso and upstream parts of Scrivia, and Orco, Figure 7) to significantly lower values (e.g. the lower part of Sesia, Tanaro and Po). Confinement ranges from partly confined (e.g. Borbera) to completely unconfined systems (e.g. the lower part of Bormida and Pellice). AC_norm provides an indication of the width of the active channel independently of basin size, and it is inversely correlated with WC_AC. Higher values of AC_norm describe multi-thread braided or wandering systems (e.g. Scrivia and Borbera), whereas lower values indicate more single-thread sinuous or meandering channels (e.g. Tanaro and Bormida, Figure 7).

Regional river-type characterization and classification

Hydromorphological indicators calculated for each of the 183 river segments (Table I) yield a quantitative evaluation of river reach geomorphic differences, and it can feed the river classification exercise. After running the Hierarchical Clustering using the six hydromorphological indicators (Table I), we cut the dendrogram to generate four clusters (see the horizontal blue line in Figure 3(vii)), which emerge as a distinct set of a first-level classification of the main river types existing in the region.

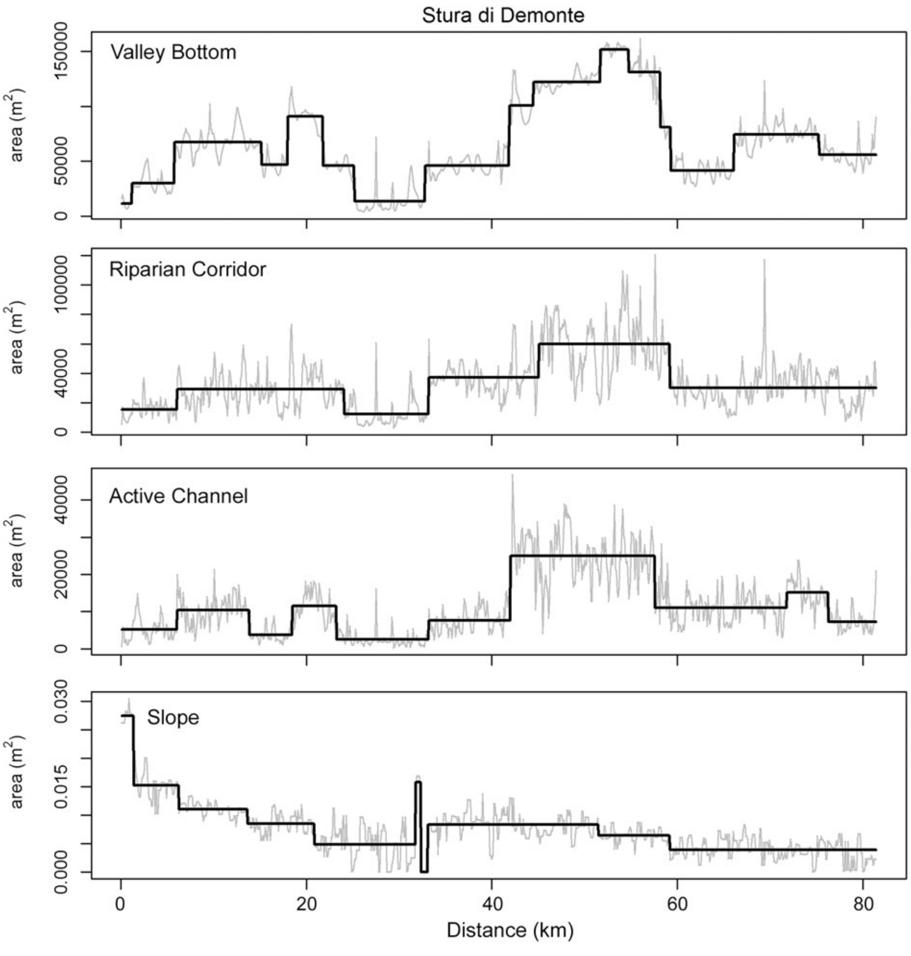

Figure 6. Example of the Hubert segmentation result for the Stura di Demonte River.

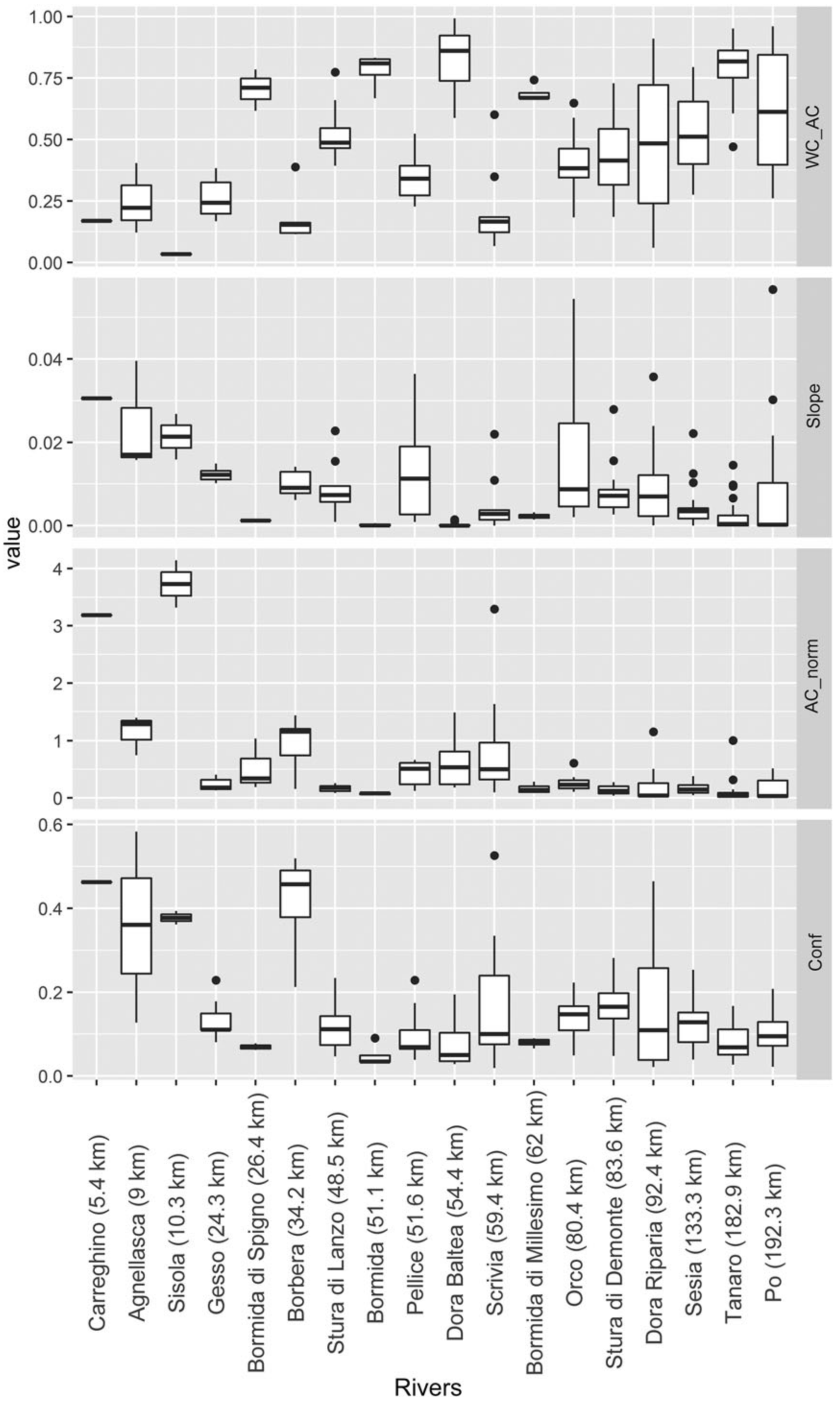

Figure 7. River boxplots describing some of the Hymo variables calculated from the RS results.

The boxplots in Figure 8 show the inner variability of the six hydromorphological indicators used for the Hierarchical Clustering, averaged for the four clusters obtained. The four clusters have been named based on the river types they describe. From left to right, there is a clear trend of increasing Slope, Sinuosity, and normalized AC width (AC_norm, Table I), as well as decreasing Sinuosity and amount of AC covered by water (WC_AC, Table I); the lower the WC area is, the higher the presence of unvegetated sediment bars (US) is within the channel. This pattern (from left to right of Figure 8) well describes a channel transition from meandering through sinuous (or transitional) towards wandering and eventually braided types.

These shifts in river configurations can be visually identified in Figure 9, where river types are mapped across the region. Moreover, looking at the orthophotos in Figure 1, distinctive channel planforms for each river type can be clearly recognized. This set of spatial and statistical tools obtained from the RS classification results is a precious and novel source of information that can aid in the understanding of hydromorphological characteristics at the regional scale and describe the different river types found in the region.

For example, in the southeast of the region, originating from the Northern Apennine, a typical braided shape, characterized by a steep channel gradient, high values of confinement, low sinuosity and WC percentage (WC_AC), describe the stream Borbera and the upper parts of the Scrivia River (see Figures 8 and 10). The Scrivia River flowing downstream shifts then to wandering and eventually sinuous before encountering the Po River (Figure 9). In the south of the Piedmont Region, the rivers Tanaro and Bormida present single-thread channels, which have been classified as meandering types alternating with

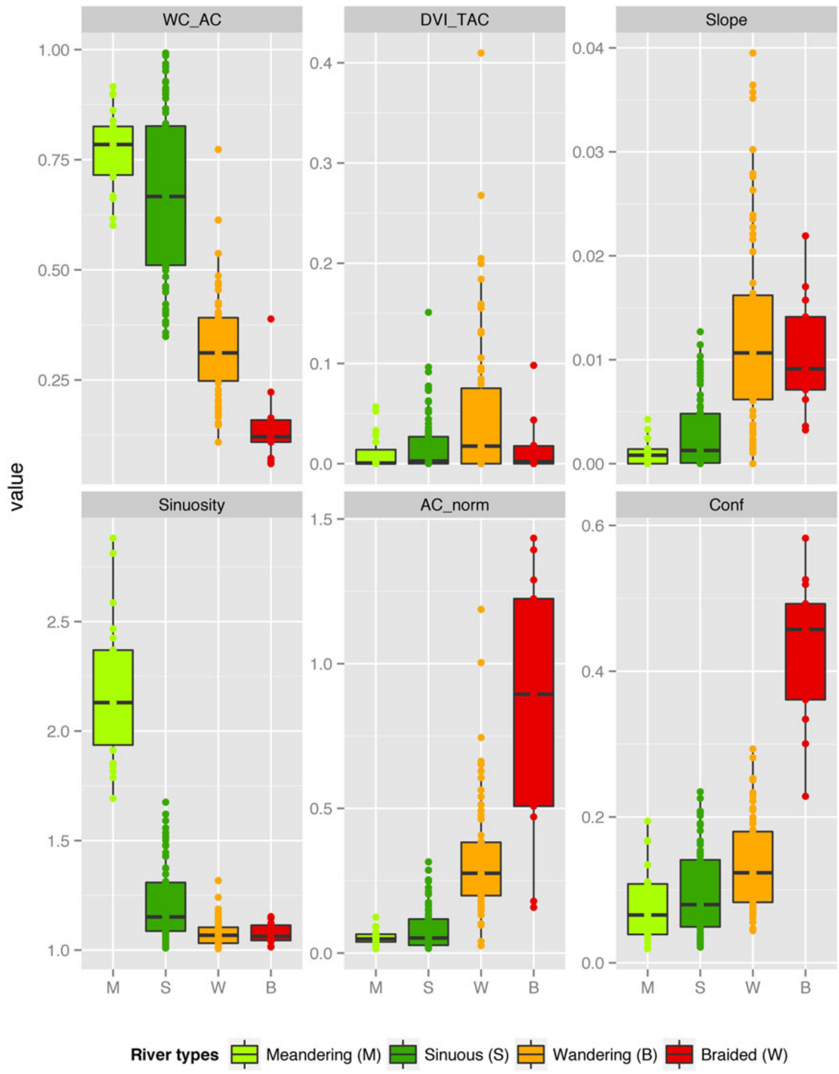

Figure 8. Boxplots of the four river types, showing the variability of the Hymo indicators used for the Hierarchical Clustering. [Colour figure can be viewed at wileyonlinelibrary.com]

sinuous reaches. They also originate from the northern Apennine and are characterized by gentler slope and unconfined channel with higher sinuosity, showing the typical landforms of meandering rivers. In this area, the spatial variability of the sinuosity seems prevalent in the distinction between meandering and sinuous river types (see the sinuosity boxplot in Figure 8). The northern rivers (Dora Riparia, Stura di Lanzo, Orco, Dora Baltea, Sesia, Pellice, Gesso and Po, see Figure 1) originate from the Alps. Most of them present a similar river pattern: from wandering to sinuous going downstream. Dora Baltea shows instead only sinuous reaches. However, here we analyzed only its lower section because the Dora Baltea flows for a significant number of kilometers in another region (Valle d'Aosta), which is not included in this work. The Po River, which is a lowland river for most of its length, is described mostly by sinuous reaches.

Geographical comparisons to highlight regional patterns and deviations

As an illustrative example to show the potential of the generated HyMo DB to highlight regional laws and deviation of reaches to them, we investigated the relationships between Active Channel width and Floodplain height with basin area, assuming a proportionality in water discharge and sediment supply with basin size as a working hypothesis to explore the deviation of each of the cases.

Figure 10(a) shows a quantitative relationship between Active Channel width and basin size (AC_W, Table I) within the region. It is possible to observe a wide range of Active Channel widths according to a given size of basin area, with reaches very wide and actively supplied in bedload sediment to fairly narrow reaches. We observe a clear trend among river types, with wider active channel widths for braided channel types and narrower widths for sinuous and meandering types. Braided reaches show a fairly robust relationship with basin area, which instead is significantly more scattered for transitional types, such a wandering and sinuous.

The spatial distribution of the active channel normalized per basin area (Figure 11(a)) is a good index of variability in bedload supply. It shows that all Alpine rivers have fairly high values, indicating rich sediment supply with the exception of Doria Riparia and Dora Baltea. The Po and the lower part of the Tanaro system also show below-average values of the same ratio.

The HyMo DB generated also provides topographic information at the regional level. Figure 10(b) plots the Floodplain height (FP_hgt, Table I) versus basin size, and Figure 11(b) maps the ratio regionally. This indicator provides a first rough assessment of the floodplain–channel topographic connectivity at the regional level. A wide range of configurations emerge at the

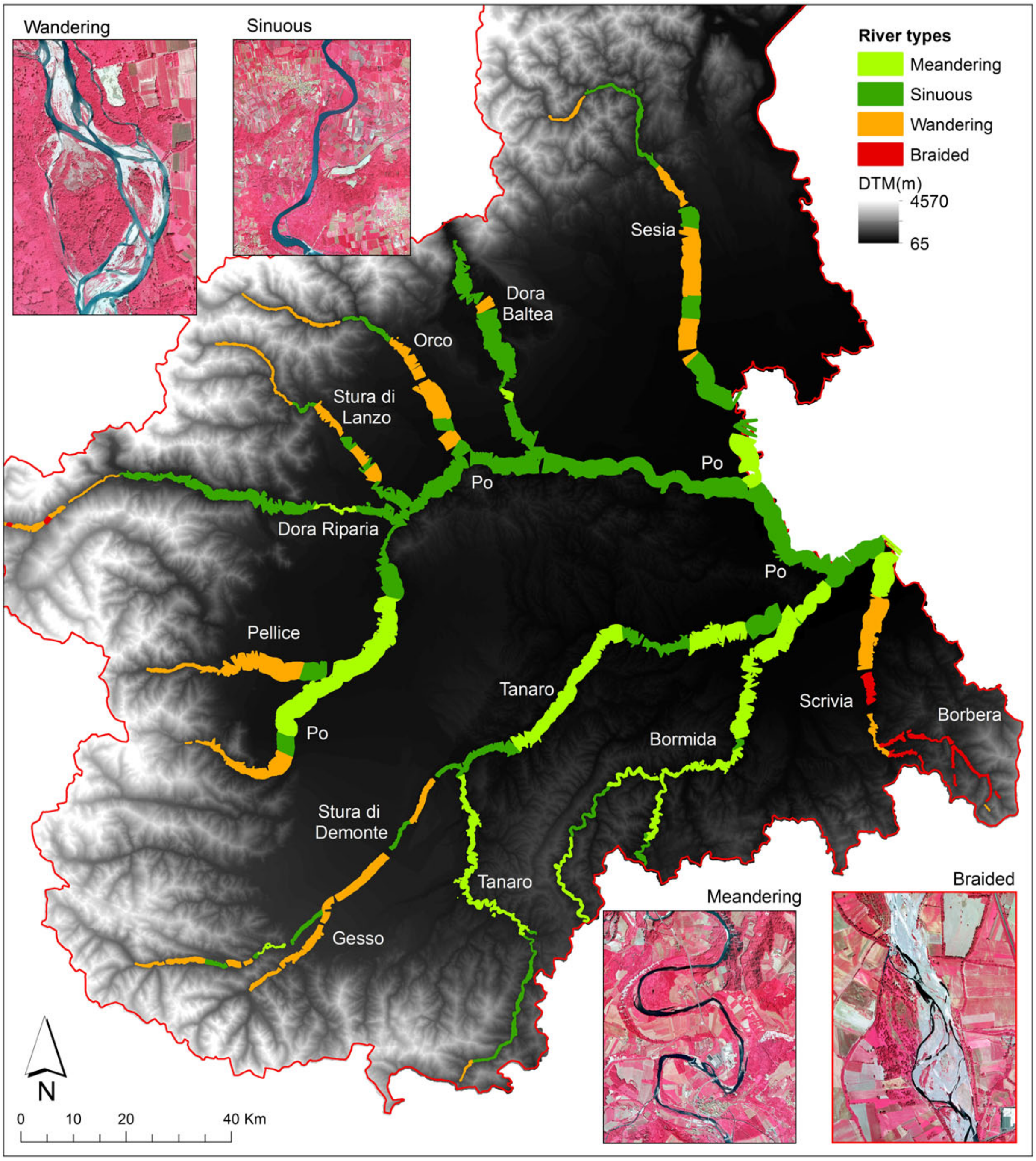

Figure 9. River-type classification for the Piedmont Region, as obtained from the Hierarchical Clustering. [Colour figure can be viewed at wileyonlinelibrary.com]

regional level, with floodplain elevation that can reach up to 7 or 9 m above the flow channel. It shows that relatively few segments have values of floodplain height below 4 m, picturing a regional setting where most channels have a high disconnection from their floodplain. Moreover, it is not possible to derive robust relationships with the basin area or per river type. We observe that, for an area greater than 100 km^2, a wide range of floodplain heights exist, and more surprisingly, the general trend is counterintuitive with channel depth, decreasing downstream. Looking at the spatial distribution of floodplain heights, we observe values above the average, particularly for the Tanaro and Bormida systems, the Stura di Lanzo and the upper part of the Dora Baltea. For Tanaro, Bormida and Dora Baltea, this deviation is also associated with a fairly low active channel width.

These diverse contexts still need to be explored and interpreted, but the observed range of variability with respect to mean conditions is already important knowledge not existing thus far to assess the regional conditions related to hydrology and sediment supply and the amount of human alterations of current river systems.

Discussion

Automatic river pattern classification method

River characterization and classification methods widely developed in fluvial geomorphology and adopted by river managers have been predominantly implemented using scattered field data and subjective expert-based interpretation of available information (Rosgen, 1994; Brierley and Fryirs, 2005; Rinaldi et al., 2013).

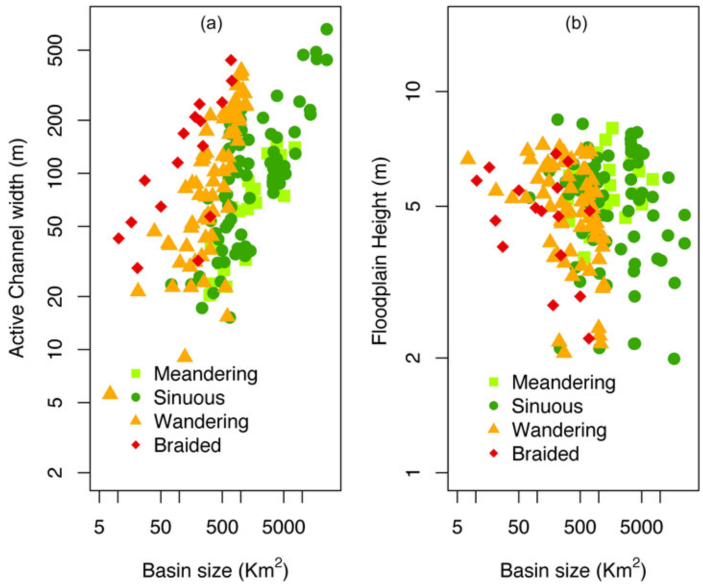

Figure 10. Relationship between AC width (AC_W, Table 1) (a) and Floodplain height (FP_hgt, Table 1) (b) with respect to Basin size for the different river types of the Piedmont Region. [Colour figure can be viewed at wileyonlinelibrary.com]

The novelty of the proposed methodology consists in the integration of spectral and topographic data at the regional scale using objective and continuous information within a multi-level geographical object-based architecture. The GEOBIA approach, combined with the SVM classifier and expert-based post-classification enhancement, proved to be a robust and flexible method to automatically distinguish different riverscape units in diverse geographical and topographical contexts across the Piedmont Region, from alpine valleys to lowland alluvial plains, from the reach to the basin.

This level of mapping has rarely been undertaken at the regional scale and represents, in this respect, a novelty. Previous works at regional scale were, in fact, mostly based on the planimetric information (Carbonneau et al., 2004, 2005; Marcus and Fonstad, 2007; Bertrand et al., 2013), except Michez et al. (2013), who focused on riparian zone characterization alone; here, for the first time, areal extent and topographic variables were generated for the key riverscape units mapped at the regional scale.

At the regional scale, we have disclosed quantitative relationships between Active Channel width and Floodplain height with respect to the basin area, a first rough assessment of the floodplain–channel connectivity describing the Piedmont Region. This is an example of how to shift from a qualitative to a more quantitative approach and therefore to process-based river characterizations, a task advocated by many research studies (Brierley and Fryirs, 2005; Carbonneau *et al.*, 2012) but so far rarely addressed, mainly due to scarcity of suitable hydromorphological information (Buffington and Montgomery, 2013). Somehow, it is the first attempt to make the river style concept of Brierley and Fryirs (2005) applicable holistically and employ it in a quantitative manner to assess the sensitivity of geomorphic features to changes.

Regional comparisons, a first approach to detect process-based anomalies

As stated by many authors and theorized by Schumm (1977), river forms are controlled by local (e.g. resistance and energy) and upstream drivers (flood regime and sediment delivery) and show a longitudinal organization. In neighboring branches of a regional network, if local and upstream drivers are similar, they should show similar patterns at a given downstream distance and a similar longitudinal channel pattern organization downstream. If not, the hypothesis of driver similarity is invalidated, or other drivers (e.g. human pressures, significant difference in the hydrological and physiographic settings) play a role. When comparing reach characters within a region, differences between them can inform potential factors driving them. This is why, following Schumm (1991), the LTS approach (Location for Condition Evaluation) can be used to explore anomalies and relate it to control factors to move from a descriptive classification to a more process-based understanding.

The transition between a braided and wandering multi-thread channel to sinuous or meandering ones described in the Results section seems essentially driven by local conditions of sediment supply and lithological, geological and climate contexts. However, the legacy of human pressures in the Piedmont Region has significantly affected sediment supply through damming and gravel mining, and then it exerts an additional important factor for determining current channel types. In the literature, the recent historical morphological trajectory of many of these rivers is well-established (Surian and Rinaldi, 2003; Pellegrini et al., 2008). In the 1950s, most of them showed multi-thread channels ranging from braided to wandering types. Then, due to decades of land use changes, in-channel gravel mining and damming in upstream catchments, many of them shifted through riverbed degradation and narrowing to single-thread sinuous patterns. Analyzing the spatial distribution of channel types therefore provides an essential baseline to start hypothesizing regarding the degree of human impacts at the regional level and supporting the design of restoration measures at the appropriate scale.

The regional maps of river types, the normalized active channel width, and the floodplain height are then useful to qualitatively detect process-based anomalies using LTS reasoning. Because geological and climate forcing are similar among alpine branches, it is possible that many reaches classified as sinuous between meandering or wandering ones, and at the same time with a fairly low active channel width and high floodplain height for a given catchment size might be affected by a higher degree of human pressures, acting on adjacent

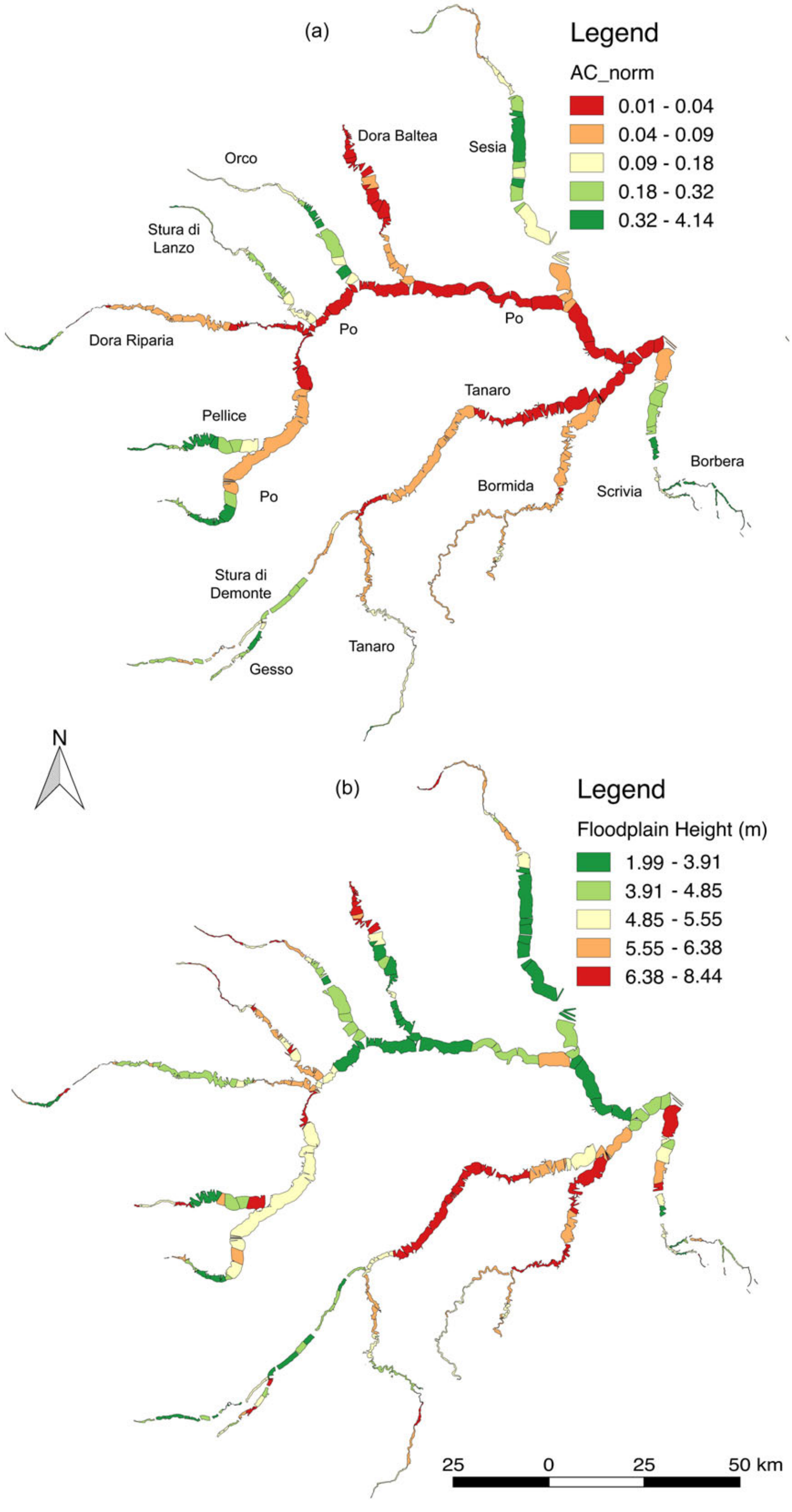

Figure 11. Spatial distribution of the active channel normalized per basin area (a) and the floodplain height (b). [Colour figure can be viewed at wileyonlinelibrary.com]

vegetation or sediment delivery and transport. They highlight areas characterized by advanced riverbed degradation, which shifted a multi-thread system (such as a wandering or braided one) into a sinuous one. The latter is a common process occurring in the Piedmont Region, well investigated in previous entries in the literature (Pellegrini *et al.*, 2008).

The reason for the deviation of Dora Riparia and Dora Baltea described in Results section has to be better investigated, but it is unlikely that it can be simply related to geological and hydrological contexts. In fact, they are not so different from surrounding alpine river systems, and therefore human-induced alteration is likely to play a role in these cases. For instance, Dora Riparia in its lower course flows through the city of Turin, and here its channel is heavily artificialized. Dora Baltea is also heavily dammed in its upstream catchment, which is not included in this analysis, flowing through the Valle d'Aosta region. Again, further analysis and field evidence are necessary to explain if these values are to be expected in this part of the region or if they are an indication of recent channel alterations related with human pressures; however, they clearly show a spatial organization that is not so coherent in terms of regional environmental setting. These values may highlight the legacy of narrowing and riverbed degradation that has occurred over the last few decades, as reported in the literature for similar river types in the center and north of Italy (Surian and Rinaldi, 2003).

If we take as reference the statistical relationships established by Piégay *et al*. (2009) on the French western Alps, we observe that some of the braided reaches of the Piedmont region are fairly active (Figure 10(a)). However, at this level of geomorphic diagnosis, it is only possible to identify process-based anomalies through geographical comparisons, but what produced the longitudinal point-change is still interpretative, and further information at the local scale is still necessary to validate this hypothesis.

When considering the channel depth (floodplain height above the low flow channel), we observe that no regional laws emerge (Figure 10(b)), and most of the reaches are significantly incised, whereas we do not consider the channel bottom as a minimum value but the low-flow water channel level. Channel incision seems to be a very important issue in this region. We still need to calibrate these preliminary results considering the potential error linked with the fact that we do not consider the channel bottom but the water level, which may more significantly affect the lower sections compared with the upper ones.

However, the results shown in Figure 10(b) and 11(b) represent at our knowledge one of the first attempts to start exploiting the topographic data for river degradation understanding at the regional scale, in spite of the relatively low topographic resolution used in the study. The channel depth values are in line with current evidence of channel trajectories in Italy, based on the review of Surian and Rinaldi (2003), which demonstrated that average riverbed incision over the last fifty years is approximately 3–4 m and in some cases can reach 10 m.

The results of this paper also show that LiDAR-derived information for characterizing topographic features of river systems at the regional level have an immense potential for analyzing patterns of river adjustment and assessing the degree of alterations and geomorphic dynamism related to sediment supply.

Integrating the HyMo DB with historical and field information to improve local-scale geomorphic diagnosis

The HyMo DB provides information at the regional scale, but this information is so detailed that it can also feed geomorphic diagnosis at a local or reach scale. In this case, the HYMO DB can then be integrated with other information available at this scale to support more detailed interpretation of on-going channel adjustment processes at the local scale, which strengthens the potential of the presented method for multiple-scale analysis. To illustrate this purpose, we focused on a section of the Orco River, which is particularly meaningful due to its recent channel dynamics and local data availability (Pellegrini *et al.*, 2008).

We analyze here all DGOs of 100 m, for a section of 30 km of the Orco River, and combined the new hydromorphological variables calculated from RS data with existing historical field-based data of Active Channel areas (e.g. Active Channel width mapped for 6 years between 1954 and 2009 and field-based cross-sections available for the years 1975 and 2003). We averaged the Active Channel area every DGO of 100 m, providing spatially and temporally distributed information. This information has been systemized in a GIS framework based on DGO segmentation and integrated within the new regional HyMo DB produced in this paper for a section of approximately 30 km of the Orco River. The difference of the interpolated averaged altitude for each cross-section series was calculated, providing an indication of the degree of riverbed incision and aggradation between these two dates (see Figure 12). The dotted line in the figure reports an indication of the areas of incision and aggradation between 1975 and 2003 based on field cross-sections.

On top of this local derived historical information, it is now possible to plot any of the regional hydromorphological variables available from the HyMo DB. This type of analysis offers a unique opportunity to confront local derived historical information with current topographical hydromorphological variables and therefore support the understanding and interpretation of current hydromorphological processes underway at the local scale. As an illustrative example, we plotted the Floodplain height and Riparian Corridor width, which includes the AC width plus its adjacent RC, composed of young and mature vegetation. It is known that historical braided channels, which shifted to more sinuous single thread typology, have been characterized by vegetation encroachment of the former AC. This can be visually appreciated in Figure 12 where reaches with the highest values of AC in the 1950s correspond to areas where the RC is currently wider. We can also observe that areas that have been widening after the 1990s now show more moderate values of the RC (compared with areas where the widening has been more moderated), and lower values of Floodplain height indicate a partial recovery of the channel–floodplain connectivity.

This illustrative example provides interesting perspectives in terms of data availability at an entire regional level for geomorphic diagnosis at the local scale. River management top-down and bottom-up approaches usually conducted with geomorphic information of different resolutions or quality (Piégay et al., 2016) should then be applied with the same type of information. National or regional levels are now able to produce, manage and deliver data that is useful for both planning their own policy and helping local managers establish local diagnosis to implement integrated catchment management plans. In the near future, sequential acquisition of LiDAR and VHR data at large scales will allow river evolution to be monitored more objectively and exhaustively, allowing a historical and regional investigation of hydromorphological variable trajectories, such as the one shown for the floodplain height in Figure 12 and potentially for all information contained in the proposed regional HyMo DB.

The topographic dataset used in this paper, although covering a large scale, was acquired at a low point density of $0.4/m^2$, which generated a DTM of 5 m in spatial resolution (with an average vertical accuracy of 30–50 cm), limiting the analysis to those river reaches where the channel width was at least 5 times larger than the spatial resolution (25 m in this case). Therefore, headwaters and minor tributary systems were neglected, as well as channels with significant overhanging vegetation. These issues might be overtaken in the near future by using LiDAR data with higher point density.

Although data accuracy poses some limitations on the exhaustive characterization of the entire river network and the potential use of this information to highlight local scale geomorphic diagnosis in the upper branches, the HyMo DB offers the possibility to start quantifying functional relationships between riverscape units and their formative drivers, such as hydrology and sediment supply at an entire regional scale for main channels, and highlighting functional patterns and human pressures to plan restoration actions.

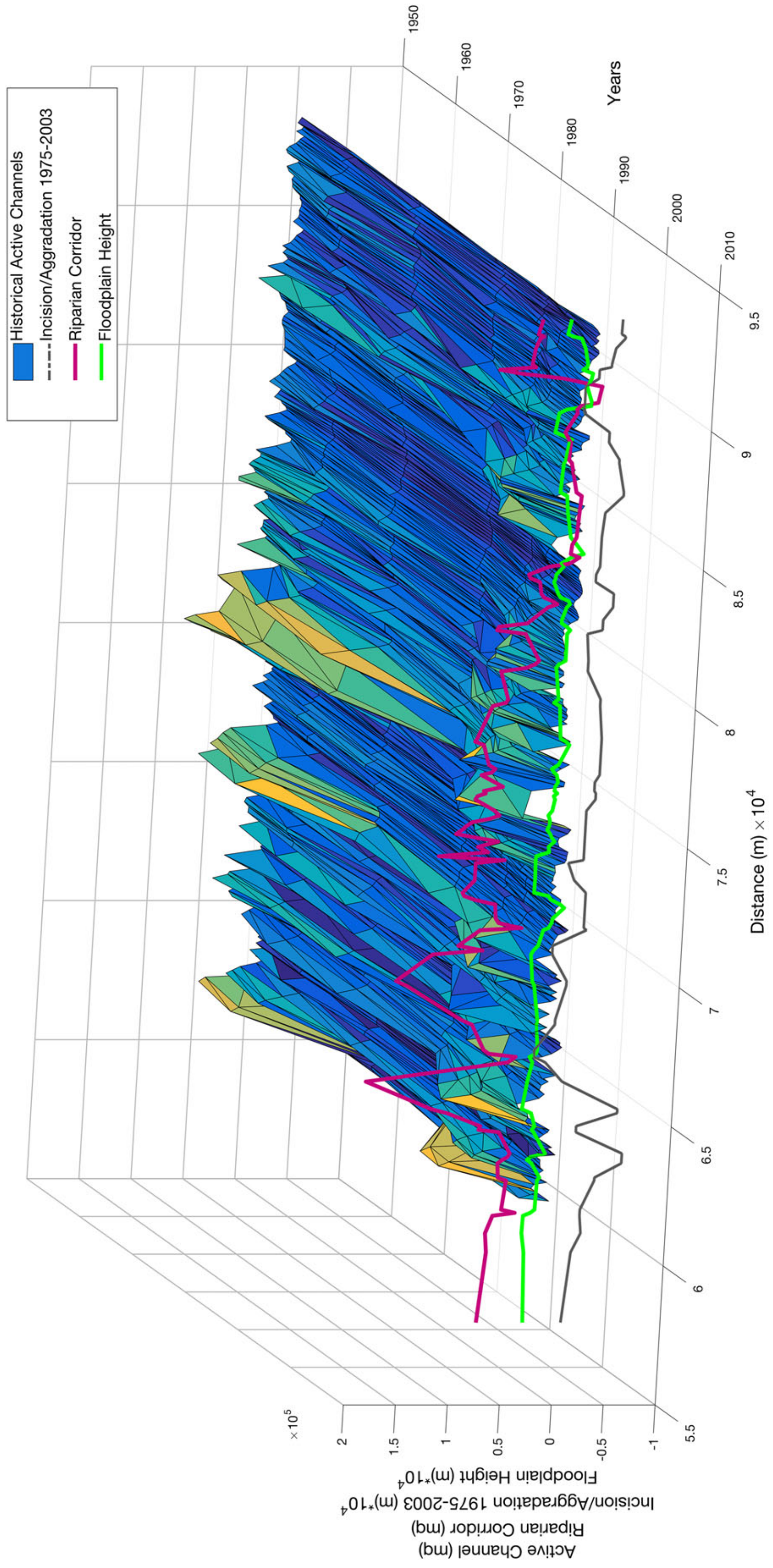

Figure 12. Reach-scale analysis for 30 km of the Orco River. Historical field-based Active Channel areas are plotted from the year 1954 up to 2009 against the Riparian Corridor and Floodplain height obtained from the Hymo DB based on RS mapping. The dotted grey line also shows the areas of incision and aggradation between 1975 and 2003 based on field cross-sections. [Colour figure can be viewed at wileyonlinelibrary.com]

Conclusion

In this paper, we presented a hydromorphological database at the regional scale using automated RS analysis of VHR and LiDAR imageries. Approximately 1700 km^2 of river floodplains have been continuously mapped at a spatial resolution of 40 cm into meaningful riverscape units with specific geomorphic meaning. This has been possible thanks to the method developed in Demarchi *et al.* (2016) and applied here to the same RS dataset, available for the entire Piedmont Region.

The resulting database (HyMo DB), composed of approximately 12 000 geographical objects (DGO) of 100 m each, allows for regional spatial and statistical analysis in a quantitative manner. Several hydromorphological variables can be continuously quantified (e.g. confinement, sinuosity, water channel percentage, etc.), offering a unique set of tools for hydromorphologists to exploit for several purposes, enriching traditional river characterization and classification practices. The high spatial resolution (40 cm) combined with the large-scale coverage (1700 km^2) allows for multi-scale analysis of the HyMo DB.

At the regional scale, river-type classification can be automated, and river types can be quantitatively characterized by a specific set of key hydromorphological drivers (Figure 8), emphasizing regional similarities and anomalies or assessing potential alterations and main geographical controls that might be related to varied types of factors (e.g. human pressures or physiographic conditions). The HyMo DB provides the basis to start an assessment of this type, aiming to quantify the degree of alterations occurring at the regional level. It is then a valuable source of information for river managers that did not previously exist. At the local scale, we have shown how to integrate the regional RS-based hydromorphological information with historical, field-based information to better understand channel processes at the local scale in a measurable way.

Currently, the availability of simultaneous LiDAR and VHR data is still rare, particularly over large areas. However, the great technological development of RS will most likely fill this gap early in the coming years. The main research challenge will therefore consist of how to translate such large amounts of big-data into meaningful indicators that are able to effectively advance our understanding of river systems. In this regard, the ability to distinguish and fully characterize riverscape units by semi-automated procedures is an essential step.

If the proposed methodology is applied in the near future to sequential RS acquisitions of topographic and spectral data, it will be possible to generate a topographic archive of hydromorphological variables measured in an objective and quantitative manner through time and continuously along extensive river networks. This will open the way to detect riverscape unit changes and then to infer the typology and magnitude of fluvial geomorphological processes of which the riverscape units represent a signature in time. This novel information would likely allow us to question established ideas in fluvial geomorphology, possibly moving towards novel categories of river types and fully process-based classification frameworks (Carbonneau *et al.*, 2012; Buffington and Montgomery, 2013). At the same time, it will be of notable value for river management to set restoration targets and foster regional visions into the design of large-scale cost-effective rehabilitation plans.

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Conflicts of Interest

The authors declare no conflicts of interest.

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