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The use of remote sensing to characterise hydromorphological properties of European rivers

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Abstract Remote sensing (RS) technology offers unparalleled opportunities to explore river systems using RADAR, multispectral, hyper spectral, and LiDAR data. The accuracy reached by these technologies recently has started to satisfy the spatial and spectral resolutions required to properly analyse the hydromorphological character of river systems at multiple scales. Using the River Hierarchical Framework (RHF) as a reference we describe the state-of-the-art RS technologies that can be implemented to quantify hydromorphological characteristics at each of the spatial scales incorporated in the RHF (i.e. catchment, landscape unit, river segment, river reach, sub-reach—geomorphic and hydraulic units). We also report the results of a survey on RS data availability in EU member states that shows the current potential to derive RHF hydromorphological indicators from high-resolution multispectral images and topographic LiDAR at the national scale across Europe. This paper shows that many of the assessment indicators proposed by the RHF can be derived by different RS sources and existing methodologies, and that EU countries have sufficient RS data at present to already begin their incorporation into hydromorphological assessment and monitoring, as mandated by WFD. With cooperation and planning, RS data can form a fundamental component of hydromorphological assessment and monitoring in the future to help support the effective and sustainable management of rivers, and this would be done most effectively through the establishment of multi-purpose RS acquisition campaigns and the development of shared and standardized hydromorphological RS databases updated regularly through planned resurveyed campaigns.

Keywords Fluvial geomorphology · River remote sensing · River characterisation · Water framework directive

Introduction

Fluvial geomorphological surveys have become increasingly popular over the last decade as a tool to support sustainable river management. They have been used effectively in the assessment and mitigation of flood risk, the design of sustainable restoration and rehabilitation projects, and in the proposition of effective measures to protect and increase freshwater ecosystem biodiversity (Brierley and Fryirs 2005; Sear et al. 2009; Davies et al. 2010). However, a reliance on field-based approaches limits their wide-spread application at the network scale which is needed to meet current regulatory obligations (Newson and Large 2006).

Fluvial geomorphology received renewed interest in Europe, and a change in name, following the Water Framework Directive (WFD) (EC 2000), which requires the evaluation of river hydromorphological status for all river systems in Europe. Considered a supporting element for biological quality, hydromorphology is defined using a selection of hydrological and geomorphological

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characteristics. hydromorphological characteristics also form a central role in the delineation of water bodies and the assignment of a river type. The ECOSTAT working group of the Common Implementation Strategy (CIS) for WFD analysed and grouped all Member State (MS)'s river typologies into macro-categories in order to facilitate their comparability in terms of ecological status: currently they define 15 river types based upon the altitude, area and geology of the river's catchment. This exercise produces a simple, high-level classification that should be integrated with detailed classifications and assessments devised by each MS. However, many MSs currently do not have an established river classification implemented at the national level. Consequently, the development of methods for characterizing and monitoring hydromorphology robustly and consistently over pan-European scale is an urgent demand of the WFD as well as a challenging research topic (Newson and Large 2006).

Most river geomorphological survey methodologies (Brierley and Fryirs 2005; Sear et al. 2009; Rinaldi et al. 2013) rely heavily on expert opinion. Surveys are still conducted predominately using field-based methods, which require time- and resource-intensive field campaigns, as well as a specific expertise in fluvial geomorphology that may not be available to authorities across Europe. These prerequisites limit *de-facto* their operative application to a limited number of rivers (rarely extended to the entire river network scale), and may call into question their appropriateness to monitoring purposes, which require an objective, repeatable assessment method. Surveys typically rely strongly on expert opinion and for this reason the conclusions drawn can be highly dependent on the surveyors experience and familiarity with the systems. It is in this context that the REFORM project developed the Hierarchical Framework (RHF), which outlines a comprehensive, flexible assessment methodology that complements and extends the official WFD guidelines for hydromorphological surveys (CEN 2004) by considering hydromorphological processes-form interactions over a hierarchy of spatial scales from the catchment down to the sub-reach (e.g. geomorphic and hydraulic units) (Gurnell et al. 2015). The RHF encourages a multi-scale approach where finer scale field data are integrated with reliable data with large spatial coverage, or in other words remotely-sensed data, to provide as far as possible a comprehensive and objective understanding of river system functioning at the basin scale.

Remote sensing (RS) technology is opening up new possibilities for river science and management (Carbonneau and Piegay 2012; Carbonneau et al. 2012). Marcus and Fonstad (2010) stress that RS techniques should be more widely applied in both science and management, but the consistent progress seen in the field means that the range of applications to fluvial geomorphology is now remarkable. Many fluvial characteristics that are commonly monitored for hydromorphological surveys have been measured in scientific studies using RS technologies, such as multispectral, hyperspectral, RADAR and LiDAR data. However due to the steep cost of data acquisition, the use of RS for river characterisation has been oriented mostly towards answering specific research questions for case studies rather than confronting aspects of operational implementation for wide scale applications, as encouraged by Marcus and Fonstad (2010). Recently, though, the acquisition of RS data covering large areas (regional or national) has started to achieve suitable spatial and spectral resolution for fluvial science. With dawning RS data availability at broader scales and suitable accuracy, the possibilities to survey and characterise extensively the hydromorphological features of river systems at multiple scales, from catchment to reaches, in Europe is unprecedented. This availability of datasets however challenges existing data analysis skills and requires sophisticated statistical modelling frameworks to become suitable for river characterisation and management (Alber and Piégay 2011; Schmitt et al. 2014).

In this paper, we outline how a deeper integration of RS data into existing river geomorphological assessments would facilitate the objective, comparable characterisation of hydromorphological status for rivers across the EU, as mandated by the WFD. Using the hierarchical approach outlined by RHF, we first identify the state-of-the-art RS technologies that can be used to quantify hydromorphological characteristics at each of the spatial scales incorporated in the RHF (i.e. catchment, landscape unit, river segment, river reach, sub-reach—geomorphic and hydraulic units) for implementation within individual river basins, nationally or across entire regions. Then we present an assessment of the availability of RS data in a selection of EU MS to facilitate a discussion of the current and potential use of these datasets for river hydromorphological characterisation. Next we discuss the data management and analysis issues that this new multi-dimensional set of information poses, which are transforming river characterisation into a data-mining problem, and provide examples of analytical methodologies to extract different components of river hydromorphology from RS data. Finally, we summarise the potentials and limitations of applying RS data to river hydromorphological monitoring, especially over a pan-European scale, as requested by the WFD.

The use of remote sensing for river characterisation

The RHF developed a list of indicators of hydromorphological condition that represent key processes operating at each spatial scale. The framework is coherent with earlier work on hierarchical functioning of river systems (e.g. Frissell et al. 1986; Brierley et al. 2013) but it focuses on how hydromorphological processes cascade down the spatial scales to impact the form and behaviour of channels. Temporal change is expressly considered in RHF in order to quantity process rates, detect changes in indicators over time, identify pressures and link pressures to hydromorphological adjustment (Grabowski et al. 2014). Uniquely, RHF also identifies the datasets that can be used to characterise the indicators, for which RS data are a primary source at most spatial scales. A brief summary of the spatial units, their geomorphological significance, and the RS data sources that can be used to characterise them are presented in Table 1; a detailed explanation of the RHF approach can be found in Gurnell et al. (2014). Our intention here is to introduce the framework as an approach to conceptualise and structure a hydromorphological assessment, and to provide an overview on how RS data can be used to support strategic data collection and improve the resulting characterisation. In this section we work our way down through the hierarchy of spatial scales matching RS datasets and analytical approaches to a selection of RHF indicators.

At the *catchment* level, pan-European datasets are available under common data formats for some indicators, particularly those related to geology and land cover (see links in Table 1). These datasets are a result of a long process of standardisation, monitoring and data processing at pan-European level, and therefore provide a consistent and reliable source of data for most MS. RS data have been central to the formation of many of these datasets. For instance the Corine datasets are the result of a European Union project that began in 1985; Corine stands for 'co-ordination of information on the environment' and it was a prototype for data collection and harmonisation to provide evidence to tackle environmental issues across Europe. The 2006 Corine land cover dataset classifies land cover into 44 classes using RS data from the SPOT-4/5 and IRS P6 LISS III satellites. The dataset is freely available from the European Environment Agency for most MS in both raster and vector formats and has a minimum mapping unit of 25 ha. The standard is a goal yet to be achieved for smaller unit scale hydromorphological indicators.

The *landscape unit* is important for understanding the hydrological responsiveness of a catchment and also its sediment source and delivery characteristics. Topography, geology, and land cover are the key characteristics used to delineate the units and to derive indicators related to the production of runoff, fine sediment and coarse sediment. Runoff production is a complex response of soil hydrological properties, parent geology, topography, land cover/use and precipitation, but can be assessed in a relative manner for the landscape units based on Corinne land cover, using level 2 classes (Gurnell et al. 2014). Soil erosion is a major source of fine sediment in river systems, so soil erosion models that couple hydrological models, land cover and soil properties maps can be used to estimate the rate of fine sediment production in landscape units (e.g. the Pan-European Soil Erosion Risk Assessment—PESERA; Kirkby et al. 2004). Coarse sediment production estimation is more challenging because of the detailed and case-specific knowledge on geology and topography needed in order to be able to locate the potential source of sediment and assess their connectivity, spatially and temporally (Fryirs 2013). Czuba and Foufoula-Georgiou (2014) build a network based framework for identifying potential synchronizations and amplifications of sediment delivery at the basin scale using simply a digital elevation model (DEM) and its derived fluvial morphological features. An attempt based on a semi-automatic procedure at the catchment scale using a DEM and multispectral orthophotos, and available geological layers was made by Bertrand et al. (2013). They modelled the potential impacts of sediment replenishment on functional units of gravel bed rivers to study the impact on habitat diversity and on trout distribution at the network scale in the Drôme River network, France. The European Landslide Susceptibility Map available from the JRC's Soil portals can also be used in an assessment of sediment delivery potential.

At the *segment* and *reach* scales, RS data have only recently been used for hydromorphological characterisation and management applications following improvements to the accuracy of topographic data (e.g. LiDAR). For example, floodplain width was characterised and its control on channel dynamics assessed continuously at the regional scale (Rhône Basin, France) using a 25 m resolution DEM to support a discussion on longitudinal, multi-scale patterns and fluvial processes (Notebaert and Piégay 2013). Recently, sophisticated semi-automated recognition tools based on detailed topographic LiDAR data have been successfully developed for the delineation of fluvial terraces and floodplain features (Stout and Belmont 2014). Furthermore, sequential LiDAR surveys can be compared to calculate sediment budgets and to investigate channel pattern changes (Flener et al. 2013; Wheaton et al. 2013; Pirot et al. 2014), which can incorporate uncertainty to improve the detection of topographic change and to derive error estimates for the sediment budget (Lallias-Tacon et al. 2014).

Riparian vegetation is both an indicator of and a control on hydromorphological functioning in rivers at the *segment* and *reach* scales. Attributes of riparian vegetation cover (e.g. extent of the riparian corridor, longitudinal continuity, patchiness, and composition) provide an insight into the morphological adjustment of the river, natural process of vegetation succession, and the level of human modification

Table 1 A list of hydromorphological indicators proposed in the RHF (Gurnell et al. 2014), which have been derived in the literature using RS data and gis processing analyses

Spatial unit	Assessed criteria	Indicators with references	RS data
Catchment	Geology	*Geological and soil type maps* (Moreover, soil erodibility, soil erosion, rockiness/stoniness degree, roughness)	http://www.onegeology.org/ http://eusoils.jrc.ec.europa.eu/ http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/
	Morphology	*Digital surface model* (ASTER GDEM, 30 m resolution 7-14 m vertical accuracy)	http://asterweb.jpl.nasa.gov/gdem.asp
		Digital surface model (Pan-EU DEM at 25 m based on ASTERGDEM, higher quality than any other publicly available DEM at EU scale)	http://www.eea.europa.eu/data-and-maps/data/eu-dem
	Landcover	*Land cover* (CORINE land cover)	http://www.eea.europa.eu/data-and-maps/data/clc-2006-vector-data-version-1
		Green vegetation fraction (fCover) of leaf area index (LAI) (Baret et al. 2013)	http://land.copernicus.eu/global/products/fcover
Landscape	Fine sediment production	*Pan/European Soil Erosion Risk Assessment model (PESERA)* (Kirkby et al. 2004)	http://eusoils.jrc.ec.europa.eu/ESDB_Archive/pesera/pesera_download.html
	Coarse sediment production	*River type changes following coarse sediment reintroduction* (Bertrand et al. 2013)	High resolution multi-spectral and DEM (25 and 50 m)
		Potential of synchronization and amplifications of sediment delivery (Czuba and Foufoula-Georgiou 2014)	DEM (30 m)
Segment	Sediment supplied to the channel	*Sediment budget* (Notebaert et al. 2009; Wheaton et al. 2013; Lallias-Tacon et al. 2014)	LiDAR
		Stream power (Barker et al. 2009; Biron et al. 2013)	LiDAR
	Sediment transport and storage		
	Valley control on channel dynamics	*Floodplain and terraces features* (Notebaert and Piégay 2013; Stout and Belmont 2014)	High resolution multi-spectral and DEM (various resolutions and sources)
	Riparian corridor features	*Vegetation Structural classes* (Johansen et al. 2007, 2010b)	High resolution multi-spectral
		Plant projective cover (Johansen et al. 2010a)	High resolution multi-spectral
		Riparian zone extent and width (Johansen and Phinn 2006; Clerici et al. 2013; Weissteiner et al. 2014)	High resolution multi-spectral
	Potential wood delivery	*Woody debris* (Marcus et al. 2002; Smikrud and Prakash 2006)	High resolution multi-spectral
		Woody debris (Marcus et al. 2003)	Hyperspectral
	Flood area	*Flood extents and flood wave dynamic* (Neal et al. 2009; Martinis et al. 2009; Pulvirenti et al. 2011)	RADAR

Table 1 continued

Spatial unit	Assessed criteria	Indicators with references	RS data
Reach	Flow Energy	*Stream power* (Barker et al. 2009; Biron et al. 2013; Bizzi and Lerner 2015)	DEM (various resolutions and sources)
	Sediment size	*Bed sediment size* (Carbonneau et al. 2004, 2005)	High resolution multi-spectral
		Bank sediment size (Rainey et al. 2003)	Hyperspectral
	Channel dimensions and features	*Channel morphology* (Notebaert et al. 2009; Biron et al. 2013)	LiDAR
		Active channel (Legleiter 2012)	LiDAR
		Active channel (Johansen et al. 2011; Bertrand et al. 2013; Fisher et al. 2013)	High resolution multi-spectral
		Water depth (Fonstad and Marcus 2005; Legleiter 2012)	High resolution multi-spectral
		Water depth (Marcus et al. 2003; Legleiter et al. 2004, 2009)	Hyperspectral
		Geomorphic features (Legleiter et al. 2002; Marcus et al. 2003)	Hyperspectral
		River infrastructures (Gilvear et al. 2004; Luo et al. 2007)	Thermal
		Water temperature (Handcock et al. 2012)	High resolution multi-spectral
			Thermal Infrared
	Lateral migration, planform changes, Bed incision/aggradation	*Lateral migration, channel pattern changes, bed incision/aggradation* (Fuller et al. 2003; Westaway et al. 2003; Notebaert et al. 2009; Wheaton et al. 2013; Pirot et al. 2014; Lallias-Tacon et al. 2014)	LiDAR and DEM (various resolutions and sources)
	Aquatic vegetation	*Algae* (Hick et al. 1998)	High resolution multi-spectral
		Submerged vegetation (Williams et al. 2003; Silva et al. 2008)	Hyperspectral
	Riparian vegetation	*Riparian corridor features* (Johansen et al. 2010a, b; Michez et al. 2013)	LiDAR and High resolution multi-spectral
	Large wood and organic debris	*Woody debris* (Smikrud and Prakash 2006)	High resolution multi-spectral
		Woody debris (Marcus et al. 2003)	Hyperspectral

Table 2 MS aerial orthophotos availability and technical specifications (NS not specified, NA not available)

State	Coverage (km^2)	Spatial res. (m)	Spectral config.	Overlapping areas (%)	Date	Coupled with	Purpose	Frequency	Data accessibility and restrictions
Austria	National (83.858)	0.2	RGB and NIR	60–80 longitudinal	2010–2013	–	LPIS	3–4 years	Ownership BMLFUW
Belgium	Flanders (13.522)	0.25(RGB) 0.40(NIR)	RGB and NIR	NA	2013 (RGB) 2012 (NIR)	–	Cartographic	1 year	Charged according to pricelist
Cyprus	National (9.250)	0.5 (satellite)	RGB and NIR	>10 transversal	2009–2014	Geoeye/ Worldv.	LPIS of the CAPO	every 1 year 20 % of Cyprus	Accessible for the CAPO
Cyprus	Main river network	0.2 (aerial)	RGB	60–65 longitudinal, 25–35 transversal	Nov 2012	LiDAR	Floods Directive Flood Hazard Mapping	NS	Accessible with no restrictions (CWDD)
Czech Republic	National (78.866)	0.25	PAN, RGB and NIR	55 longitudinal, 20 transversal	2009–2014	–	Topographic	2 years	Charged according to pricelist
Finland	National (303.890)	0.5	RGB and NIR	NA	2004–2014	–	Topographic	NS	Accessible with no restrictions since 2008 (NLSF)
France	National (551.695)	0.25	RGB	NA	2013–2014	–	Cartographic	NS	Accessible with no restrictions
France	National (551.695)	0.50	RGB and NIR	NA	2013–2014	–	Cartographic	NS	Accessible with no restrictions
Germany	National (357.168)	0.25–0.5	RGB	NA	2011–2014	–	Cartographic	NS	Charged according to pricelist
Italy	National (301.338)	0.5	RGB	NA	2009–2012	–	Cartographic	NS	Free for non-commercial use
Netherlands	National (41.543)	0.5 or 0.1	RGB	NA	2014	–	Cartographic	1 year	Charged according to pricelist
Norway	National (350.000)	0.5 (before 2012)	RGB	>10 transversal	2009–2014	–	Topographic	5 years	Charged according to pricelist
Norway	National (350.000)	0.25 (after 2012)	RGB	NA	2009–2014	–	Land use	NS	Charged according to pricelist
Poland	National (312.679)	0.25	RGB	NA	2013	–	NS	NS	Symbolic fee
Poland	Urban areas	0.1	RGB	NA	2013	–	NS	NS	Symbolic fee
Portugal	National (92.212)	0.5	RGB and NIR	NA	2004–2006	–	Cartographic	NS	NS
Romania	National (238.391)	0.5	RGB	45 longitudinal	2007–2012	LiDAR	Topographic	NA	Under agreement with the RWNA
Spain	National (505.992)	0.25–0.5	PAN, RGB and NIR	60–65 longitudinal	2010–2012	–	Topographic	2–3 years	Free for non-commercial use
Sweden	National (449.964)	0,5 (0.25 m urban)	PAN and RGB	>20 transversal	2006–2014	–	Land use	2 years (RGB) 10 years (PAN)	Free for non-commercial use

BMLFUW Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management, *CAPO* Ministry of Agriculture, Natural Resources and Environment and for the Ministry of the Interior, *CWDD* Cyprus Water Development Department, *NLSF* National Land Survey of Finland, *RWNA* Romanian Waters National Administration, LPIS Land Parcel Identification System to the floodplain. Mapping riparian vegetation attributes is an established field of research, in which multiple types of RS data have been used to identify and characterise vegetation. Whilst much research has been conducted using aerial imagery and multispectral data, Johansen et al. (2010b) found that discrete return LiDAR is more cost-effective than QuickBird and SPOT-5 data for mapping riparian zone attributes over long river networks (26,000 km of stream length in this study). Moreover they found that SPOT-5 data were not useful for mapping most of the riparian attributes because of its coarse spatial resolution (pixel size = 10 m). More recently, Michez et al. (2013) developed automated tools to quantify key riparian zone attributes for the assessment of the ecological integrity of the riparian zone at a network scale from a single aerial LiDAR dataset (Houille River, Belgium). This type of analysis offers the possibility of expanding the assessment of riparian zone vegetation to the entire Flanders region, which was completely mapped in 2014 with aerial LIDAR (13.000 km). Also, average riparian corridor width has been calculated across Europe by Weissteiner et al. (2013) from Landsat ETM+ imagery and the ASTER DEM based on an improved riparian area detection model (Clerici et al. 2013). The estimated riparian corridor width was used to assess the buffering capacity of riparian areas for nutrients and pesticides (Weissteiner et al. 2013, 2014).

At the segment scale, Synthetic Aperture Radar (SAR) represents an alternative to optical imagery, aerial photography and hydraulic models for mapping flood extent over large areas. SAR data has almost complete worldwide spatial coverage, can be easily analysed to segment surface water from land, and benefits from frequent resurveying (the exact timing of which depends on the satellite used). This opens the door for important management applications, including improved prediction of flood wave dynamics to inform better, more targeted flood hazard assessment (Neal et al. 2009). The recent launch of satellites carrying high-resolution SAR (<5 m), such as TerraSAR-X, RADARSAT 2 and the COSMO-SkyMed, promises further applications in this direction in the near future (Bates 2006). Moreover new algorithms like Persistent or Permanent Scatterer (PSInSAR) techniques permit the measurement of movement in a single pixel over time with millimetre-scale precision, and have begun to be exploited in the study of rockslide activity and kinematics and the analysis of damage to buildings (Frattini et al. 2013). Given recent improvements to data accuracy, spatial coverage, and resurvey frequency, it represents a potential and yet unexplored resource for monitoring channel morphological dynamic at a variety of scales.

At the *reach* scale, many key hydromorphological features can now be derived with semi-automated procedures based on LiDAR data and high-resolution multispectral orthophotos. Channel slope can be measured at the network scale with accuracy comparable to field surveys from a 5 m resolution LiDAR DEM (Biron et al. 2013). Channel widths can be measured from freely-available aerial imagery (e.g. Google Earth; Fisher et al. 2013), calculated automatically from LiDAR data (Legleiter, 2012), or estimated from high-resolution multispectral data based on the delineation of low-flow water channels and unvegetated bars (Bertrand et al. 2013). By coupling channel gradient and active channel width measurements with hydrological models, total and specific stream power can be calculated continuously along a river course (Barker et al. 2009). These advances are permitting the development of screening tools for river sensitivity to erosion and deposition processes at the network scale (Biron et al. 2013; Bizzi and Lerner 2015). However, it is worth bearing in mind that estimates of active channel width using RS may have limited geomorphological relevance as they are based on the water surface at the time of data acquisition. Unless the campaign was timed to a specific high flow event, they will not provide information on the width of the channel at the discharge which is believed to have the most impact on channel morphology (i.e. bankfull discharge). The quantification of bankfull channel width with RS data is still problematic and an open issue in research since its assessment requires detailed knowledge of the channel topography and associated morphological features. For this reason its calculation often need to be integrated by field-based knowledge. The identification of river infrastructures, like bridges, roads and railways can also partly automated by RS data (Gilvear et al. 2004; Luo et al. 2007).

At the sub-reach scale, geomorphic units, large wood, water depth and bed sediment sizes have been measured from high-resolution RS data (Westaway et al. 2003; Legleiter 2012, 2014). For example, image texture has been used successfully to estimate bed sediment size as areas with larger sediment have more shadows, which suggest a more heterogeneous texture (Carbonneau et al. 2004, 2005; Buscombe et al. 2010). Hyperspectral data have been particularly useful at this scale. For instance Marcus et al. (2003) used 1-m resolution, 128-band hyperspectral imagery to map in-stream habitats and found very high correlations with field derived measures. Interestingly, the study concluded that “accuracy estimates for the in-stream habitat and wood mapping may have been misleadingly low because the fine-resolution imagery captured fine-scale variations not mapped by field teams, which in turn generated false ‘misclassifications’ when the image and field maps were compared”. This provides an idea of the potential challenges of using such techniques for assessment purposes. For water depth, multispectral and hyper spectral images have be analysed using a band-ratio to map

Table 3 MS topographic LiDAR availability and technical specifications (NS not specified, NA not available)

State	Coverage (km^2)	Point density (pt./m^2)	LiDAR derived products (res.)	Date	Coupled with	Purpose of acquisition	Frequency of acquisitions	Data accessibility and restrictions
Austria	National (83.858)	1–20	DEM, DSM	2003–2013	–	Government	Hot-Spot Updates after first cover	Partnerships with federal governments
Belgium	Flanders (13.522)	NS	DEM (5 m)	2013–2015	–	NS	1 year	NS
Cyprus	Main river network	1	LAS, DEM, DSM (5 m)	Nov 2012	Aerial orthophotos	Floods directive/flood hazard mapping	NS	Free for non-commercial use
Czech Republic	National (78.866)—in progress	1	DEM, DSM (5 m)	2009–2014	–	Topographic	NS	Charged according to pricelist
Denmark	National (42.916)	4	DEM, DSM (0.4 m)	2008–2013	–	NS	NS	NS
UK	72 % of England and Wales (93.884)	0.5–16	DEM, DSM (2–0.25 m)	2010	–	NS	NS	Free for non-commercial use
Finland	National (235.000)—in progress	0.5	DEM (2 m)	2008–2014	–	Topographic	NS	Free for non-commercial use
Italy	Main river network	NS	DEM (1 m)	2008–2009	–	Topographic	NS	Symbolic fee
France	National (551.695)	NS	DEM (1 m)	NS	–	Topographic	NS	Free for non-commercial use
Netherlands	National (40.000)	9	LAS, DEM, DSM (0.5 m)	2007–2012	–	Topographic	6 years	Free for non-commercial use
Norway	Main river network (130.000)	1	DEM, DSM	2005–2014	–	Floods directive/flood hazard mapping	NS	Charged according to pricelist
Poland	National (312.679)	4	LAS	2013	–	Floods directive/flood hazard mapping	NS	Symbolic fee
Poland	Urban areas	12	LAS	2013	–	Urban studies	NS	Symbolic fee
Romania	National (106.469)	0.2–4	DEM, DSM (5–0.5 m)	2007–2012	Aerial orthophotos	Topographic	NS	Free after agreement with RWN
Spain	National (504.645)—in progress	0.5	DEM, DSM (5 m)	2008–2014	Aerial orthophotos	NS	NS	Free for non-commercial use
Sweden	National (449.964)	1–2	DEM, DSM (2 m)	2013	Aerial orthophotos	River and lakes characterization	NS	Free for non-commercial use

RWN Romanian Waters National

bathymetry (Legleiter et al. 2004), and more recently spectrally-based depth retrieval has been examined in greater detail using radiative transfer models and field spectroscopy to establish the range of conditions under which this approach would be most appropriate (Legleiter et al. 2009). River bathymetry can also be assessed using shorter green wavelengths LIDAR capable of penetrating through the water column to the bed. These LiDAR systems, also called bathymetric LiDAR, were originally designed for coastal environments and have been applied to rivers only recently (Bailly et al. 2012). However, most existing bathymetric LiDAR yield a relatively coarse spatial resolution due to a large spot size and spacing and thus are not well suited to small-to medium-sized channels (Hilldale and Raff 2008).

Pan-European examples of RS data availability for river hydromorphological characterisation

Despite a 2007 EU directive encouraging MS to establish a common Infrastructure for Spatial Information in the European Community (INSPIRE) (EC 2007), it is difficult to obtain information on the current coverage of RS data at the national scale for each MS. The INSPIRE geoportal, established as a means to disseminate this information, is not complete at present, and information is often more readily available from national geoportals, though these can be difficult to find or navigate. Therefore we conducted an informal survey of MS environmental agencies and geoportals to assess RS data availability over Europe. The aim is to evaluate the current potential to derive RHF hydromorphological indicators from high-resolution multispectral images and topographic LiDAR at the national scale. The results of the survey are limited to those MS that positively responded to the questionnaire. Details of the technical specifications by MS for these two datasets can be found in Tables 2 and 3.

Most of the countries surveyed have preferred to use aerial orthophotos to update their national geographical database, and most have used this data source to survey their entire national territory recently (Table 2). The only exception is Cyprus, which relied on satellite acquisitions at 50 cm for the national scale and a more detailed set of aerial orthophotos for the main national river network (20 cm resolution). Overall, all countries collect orthophotos at a spatial resolution of 0.5 m or better. Some MS achieved very high spatial resolution, such as the Netherlands (10 cm for the whole territory—41,543 km^2), Austria (20 cm for the whole territory—86,000 km^2), Czech Republic (25 cm for the whole territory—78,866 km^2), Norway (25 cm for the whole territory—385,178 km^2) and Poland (25 cm for the whole territory—449,964 km^2). In some cases a high longitudinal acquisition overlapping (>50 %) was respected to allow for the generation of stereoscopic DEMs (Deilami and Hashim 2011). Most of the orthophoto campaigns were conducted with the sole purpose of creating a visual cartographic reference of the highest possible detail. For this reason, the images are composed only of the visible bands. The near infrared (NIR) band was acquired by only seven MS. NIR data are essential for the characterisation of some hydromorphological indicators (Table 1), most notably those related to riparian vegetation, and their omission from national databases poses limitations on hydromorphological assessment and monitoring strategies.

Many of the MS surveyed have a national coverage of LiDAR data (Table 3), though acquisition for the whole territory is still in progress for some (e.g. Czech Republic, Finland, Spain and Slovenia) and should be completed by 2014–2015. Other countries do not have national datasets, but still have LiDAR coverage for large proportions of their territories. For example, the United Kingdom and Slovenia are limiting their acquisitions to specific target areas (ca. >70 % of their territory), whilst Norway and Cyprus are limiting theirs to the main river networks. As a result, more than 75 % of the European territory is currently covered by LiDAR data, with a density of LiDAR point returns for the datasets ranging from 0.5 to 16–20 points/m^2. Point return density has important implications for the final spatial resolution of a digital terrain model (DTM) or digital surface model (DSM) interpolated from LiDAR data. When planning an acquisition campaign, a higher density of points (e.g. more than 10/m^2) demands more flight hours, which increases the cost of acquisition. For this reason, where possible some countries have acquired LiDAR data with higher density of points only in some specific locations (such as in Polish cities, where the density of points used is 12/m^2). However, even with the lowest density of points (0.5/m^2), it is still possible to extract DTM and DSM at a high spatial resolution of 2–5 m, depending on the interpolation technique used. Most MS have these two final products (DTM and DSM) already available, apart from Finland (only DTM) and Poland (only raw las files). This means that there is already a good level of topographical detail, which would allow for the characterisation of some of the morphological indicators listed in Table 1 at almost pan-EU scale (e.g. channel dimensions and features, valley controls on channel dynamics, etc.). Some countries (e.g. the Netherlands, Poland and Cyprus) also have the original las files, which contain the laser point cloud returns, offering the possibility of exploiting the LiDAR signal beyond the extraction of DTM and DSM products, e.g. characterisation of riparian vegetation structure (Bertoldi et al. 2011). Furthermore, in most cases these data are free to non-commercial use or under agreement with local authorities, and therefore ready to be exploited for any environmental application of non-commercial purpose. However, it is worth pointing out that only the Netherlands and Belgium plan to update the LiDAR dataset regularly, every 6 and 1 year, respectively. Re-acquisition of RS data is essential to monitoring changes in hydromorphology over time, to quantifying rates of hydromorphological processes, and to assessing the success of management measures (Wheaton et al. 2013; Lallias-Tacon et al. 2014).

Only a few MS acquire LiDAR and aerial-orthophotos simultaneously (Cyprus, Romania, Spain and Sweden). In the case of Sweden, this is because the main scope of acquisition was for hydromorphological characterisation of river and lakes. This is the only MS, amongst the ones surveyed, where RS techniques are already implemented for hydromorphological characterisation. For all other MS, LiDAR acquisitions were mostly conducted for topographic purposes or, in some cases, to respond to the European Floods Directive. The lack of synchronous LiDAR and aerial orthophotos acquisitions limits significantly the potential for hydromorphological characterisation, since some indicators listed in Table 1 require high-resolution multispectral information, which can obtained from orthophotos, whilst for many others topographic information is essential. This can cause problems, especially for highly dynamic river systems, for which topographic information may not match the spectral information if they are acquired at different dates, particularly if a large flow event occurred within the acquisition period. Therefore, simultaneous acquisition campaigns are encouraged to better exploit RS data for hydromorphological characterisation.

Discussion

RS technology provides an unprecedented amount of information, which creates challenging research issues due to the multi-dimensionality and large size of these datasets. In hydrology, where suitable accuracy for continental scale applications have existed for several years, data management issues are well known (Lehner and Grill 2013) and various types of continental-scale assessments already exist from drought severity analysis (Sheffield et al. 2012) and flood pattern simulations under climate change scenarios (Dankers and Feyen 2009; Van Der Knijff et al. 2010), to world-wide forest mapping (Hansen et al. 2013). The development of RS-based assessment and monitoring at the national and continental scale, as required by the WFD, could build easily from this foundation as much of the basic data acquisition, management and analysis issues are common. Although we have shown that many relevant hydromorphological indicators can now be derived from RS, applications to large spatial areas are limited by logistical and technical difficulties and the availability of well-tested, easily-accessible automated and semi-automated data analysis procedures.

Data availability in Europe, as this research highlighted, has already reached a good level of detail, sufficient to support hydromorphological assessment for WFD. However, following our investigation at pan-EU level there are some opportunities to easily increase the potential of RS data for river hydromorphological characterisation further: (1) the coupled acquisition of topographic and multispectral information; and (2) the establishment of a regular resurveying plan. First, the absence of the NIR band for aerial orthophotos and the lack of simultaneity with topographic acquisitions for most MS pose a limitation to an effective implementation of RS techniques within the RHF. Second, river systems change over time, and a regular surveying campaigns will detect and quantify those changes which will help inform process-based understanding and management of the river. To this end, environmental agencies, water authorities and river managers across Europe must design coordinated, cost-effective acquisitions campaigns of RS data at regional/national levels. To do this, agreements would need to be made in the near future concerning the types of RS data to be collected and the frequency with which to collect them. The fact that, until now, RS datasets have been collected independently for specific purposes (see Tables 2, 3) highlights the value of finding synergies with other environmental management needs, so that costs of RS acquisition campaigns and database resource can be shared within and amongst MS.

However, an aim of increased cooperation and efficiency is not sufficient, and further work needs to be done to harmonise data acquisition and analysis, which are affected by a host of technical and logistical difficulties. Even calculating hydromorphological indicators based on established RS approaches can present significant limitations: e.g. sun glint on water surfaces and shadows cast across the river channel by riparian vegetation, high banks, and buildings are the cause of most misclassification errors in automated procedure (Gilvear et al. 2004). Small streams, rivers in gorges and turbid water can severely limit assessment and monitoring based exclusively on RS. For this reason, field geomorphological surveys are still needed to support and integrate with hydromorphological surveys conducted using RS data. It is also important to support the development of alternative techniques to estimate hydromorphological characteristic from different RS data sources to test their robustness and ensure results are consistent with field surveys. For example, Whited et al. (2013) classified salmon habitat suitability using multispectral Landsat imagery and global terrain data (90 m resolution) encompassing over 3,400,000 km^2, and then compared the results with a classifications derived from finer scale (i.e. ≤2.4-m resolution) remote sensing data for a subset of the study area. In this way they were able to evaluate the suitability of lower resolution data for habitat assessments and expand the potential application of RS-based approaches. A diversification of techniques and approaches would provide Europe with more flexibility in data acquisition options, more capability for monitoring features more frequently and across larger areas, and more opportunity for validation of results by assessing congruence between characterisations derived from different data sources and analytical methods.

When adopting a remote sensing based approach even the delineation of river reaches can be problematic, as it requires a transferable method based on consistent, spatially-continuous data that is applicable to a wide range of river types. Delineation would normally be done based on the expert judgment of a fluvial geomorphologist according to river-specific longitudinal variations in geomorphological forms and drivers. Whilst RS may form a part of their assessment, it becomes the focus when extending the delineation to the river network, basin or national scale. With the introduction of multispectral high resolution RS information, the delineation of river segments and reaches becomes a data mining task based on virtually continuous multi-dimensional data along the river channel. To do this, automated or semi-automated procedures are needed to identify and classify geomorphological features (Alber and Piégay 2011; Stout and Belmont 2014; Tarolli 2014). Significant progress has been made in this area of research recently. For example, Leviandier et al. (2012) compared statistical algorithms for detecting homogeneous river reaches along a longitudinal continuum using active channel width. Parker et al. (2012) developed a river segmentation based on stream power. Other authors have proposed multi-dimensional river segmentation based on multiple hydromorphological drivers like active channel width, slope and channel confinement to automatically identify reaches with similar geomorphic properties (Bizzi and Lerner 2012; Schmitt et al 2014). Alber and Piégay (2011) have proposed an entire framework for aggregating and disaggregating virtually continuous hydromorphological variables for characterizing fluvial features at the network-scale. Based on this framework Roux et al. (2014) have developed the "Fluvial Corridor" ArcGIS toolbox, a package for multiscale riverscape exploration. The development of semi-automated procedures to analyse hydromorphological data from RS has the potential to enhance objective, comprehensive river characterisation for European MS.

Conclusion

RS technology is transforming our capacity to analyse river systems (Marcus and Fonstad 2010; Carbonneau et al. 2012) by increasing the spatial coverage of the morphological information gathered by field campaigns. As a result we have entered an era where data can be considered 'virtually' continuous along the river channel. This paper has shown that many of the assessment indicators proposed by the RHF can be derived by different RS sources and existing methodologies, and that EU countries have sufficient RS data at present to begin their incorporation into hydromorphological assessment and monitoring. Further work, though, is needed to advance automated and semi-automated analytical approaches sufficiently to ensure that this is done in a robust and consistent manner. When this has been achieved, RS-derived indicators of hydromorphology will provide researchers with a reliable database to quantify process-form relationships that would support the development of improved quantitative models of river behaviour.

It is worth emphasising, though, that RS data will never substitute the wide range of data sources that currently contribute to the accurate assessment of current river behaviour, geomorphological sensitivity and the evaluation of future trajectories (Simon and Rinaldi 2006; Liébault et al. 2013; Grabowski et al. 2014). Expert interpretations, field surveys and historical analysis will remain important ways of reading the landscape (Brierley et al. 2013), but RS data will support and corroborate conclusions drawn from these sources. Soon, lines will blur further as the ever-growing temporal record of RS data will allow historical analysis to be conducted based on semi-automated procedures and virtually continuous data.

RS data can support the hydromorphological assessment and monitoring of European rivers as mandated by WFD, which so far have been insufficiently addressed by the member states due to the demanding efforts it would require (Newson and Large 2006). This aspect is particularly crucial in Europe, because, according to the first WFD River Basin Management Plans submitted by member states, hydromorphological alterations together with water pollution from diffuse sources are the main barriers to the achievement of the good ecological status by 2015 (European Environment Agency 2012). With cooperation and planning, RS data can form a fundamental component of hydromorphological assessment and monitoring in the future to help support the effective and sustainable management of rivers, and this would be done most effectively through the establishment of multi-purpose RS acquisition campaigns and the development of shared and standardized hydromorphological RS databases updated regularly through planned resurveyed campaigns.

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