State of Science

Remotely sensed rivers in the Anthropocene: state of the art and prospects

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ESPL
Earth Surface Processes and Landforms

ABSTRACT: The rivers of the world are undergoing accelerated change in the Anthropocene, and need to be managed at much broader spatial and temporal scales than before. Fluvial remote sensing now offers a technical and methodological framework that can be deployed to monitor the processes at work and to assess the trajectories of rivers in the Anthropocene. In this paper, we review research investigating past, present and future fluvial corridor conditions and processes using remote sensing and we consider emerging challenges facing fluvial and riparian research. We introduce a suite of remote sensing methods designed to diagnose river changes at reach to regional scales. We then focus on identification of channel patterns and acting processes from satellite, airborne or ground acquisitions. These techniques range from grain scales to landform scales, and from real time scales to inter-annual scales. We discuss how remote sensing data can now be coupled to catchment scale models that simulate sediment transfer within connected river networks. We also consider future opportunities in terms of datasets and other resources which are likely to impact river management and monitoring at the global scale. We conclude with a summary of challenges and prospects for remotely sensed rivers in the Anthropocene. © 2019 John Wiley & Sons, Ltd.

KEYWORDS: remote sensing; GIS, drone; fluvial geomorphology; biogeomorphology; channel changes; riparian vegetation; sediment transport modelling; grain size: fluvial corridor

Introduction

The concept of the Anthropocene proposed by Crutzen (2002) suggests that the geophysical influence of humans on Earth is such that we have fundamentally modified global landscape characteristics and entered a new era. Humans are changing the world's ecosystem processes and functioning, and need to adapt to the consequences of these changing conditions. With the 'Great Acceleration' of landscape changes since the 20th century (Steffen *et al*., 2007), it has become crucial to characterize evolutionary trajectories of Earth's environments in order to infer future conditions. Even though the concept of the Anthropocene is still debated, there is a pressing need to quantify the human impacts on physical systems in recent decades. Moreover, the concept of the Anthropocene also helps identify the driving processes of landscape change (Moore, 2015). Thus, although the concept focuses predominantly on large

spatiotemporal scales, human societies produce different types of change, and not all regions of the world follow the same trajectories. In other words, multi-scale approaches are needed to explore the characteristics of the Anthropocene from local to global scales. Lastly, the concept of the Anthropocene also highlights the key principles of rehabilitation and restoration as tools to preserve our landscapes and their ecological integrity.

The Anthropocene is notably of interest for river scientists and fluvial geomorphologists who explore future changes and are engaged in management applications and decision-making support. Comprehensive reviews of research on river morphology and riverine environments in the Anthropocene have been recently proposed by Downs and Piégay (2019). The Anthropocene reshapes river management perspectives by encouraging conservation and restoration processes and introduces humans as a boundary condition to be taken into

account in the definition of management options (Mould and Fryirs, 2018). The concept also suggests that fluvial systems are now socioecological hybrids and that human constructions can be perceived as potentially valuable, as is discussed with the novel ecosystem concept (Hobbs *et al.*, 2006). There is an urgent need to work on highly modified river systems and not only the most natural systems, in order to understand the physical processes and improve their functioning (Thorel *et al.*, 2018). Fluvial geomorphologists have made considerable progress in reading the landscape (Fryirs and Brierley, 2012), interpreting the range of past channel processes, understanding the biophysical and anthropogenic drivers of channel trajectories, and predicting future changes (Brierley *et al.*, 2013; Wohl, 2013; Brown *et al.*, 2018). However, our ability to quantify interactions between local hydromorphological processes and fluvial system functioning at the basin scale is still largely conceptual (Fryirs, 2013; Bracken *et al.*, 2015), as is our ability to predict likely future channel trajectories (Surian and Rinaldi, 2003; Brierley and Fryirs, 2008; Dufour and Piégay, 2009). Recent scientific contributions are emerging in this domain based on geospatial resources (Schmitt *et al.*, 2018b; Grill *et al.*, 2019). Factors that influence evolutionary trajectories can be natural or anthropogenic and may act at both reach and catchment scales; they can be progressive (e.g. climate or land use change), sudden (e.g. floods, earthquakes) or discontinuous, e.g. either a transient (e.g. sediment mining) or a permanent disturbance (e.g. dam, bank protection), forming a complex set of drivers (Dufour and Piégay, 2009). A temporal analysis of past river processes and natural inheritance is necessary to understand present river conditions, sensitivity and resilience (Brierley and Fryirs, 2005; Gurnell *et al.*, 2016; Brown *et al.*, 2018) and to support river restoration and management (Grabowski *et al.*, 2014). In the context of the Anthropocene, one of the major challenges is to isolate the role of natural and anthropogenic driving forces on past and present river trajectories to anticipate future change. Local changes (flooding, erosion, ecological alteration, water resource availability) must always be considered with an integrated catchment perspective (Figure 1). Fluvial changes are not only driven by water and sediment but also by changing vegetation and human interactions in a fairly complex system of drivers, pressures and impacts. The assessment of river status, trajectory and functioning requires a space–time framework much broader than the one employed traditionally by river engineers and managers. A complete understanding of fluvial trajectories cannot only come from the field, even if geomorphology has a long tradition of field-based investigation, because of the temporal and spatial limitations of field data. Understanding the Anthropocene is therefore intimately linked with remote sensing (RS). Recent advances in RS have produced a step-change in the spatial and temporal scales of data that can be used to characterise the impacts of humans on river systems.

The science of RS includes a range of techniques and methods to acquire information about spatial objects (e.g. a river corridor and its associated features and characteristics) and phenomena (river processes and changes) without any physical contact. It includes sensors (digital cameras, video cameras, thermal-, infra-red-, hyper- and multi-spectral sensors, light detection and ranging (LiDAR), ground-penetrating radar (GPR) or geophones) mounted on platforms (satellite, airborne, or even ground); see details on fluvial RS in Carbonneau and Piégay (2012) or more recent publications (Gilvear *et al.*, 2016; Entwistle *et al.*, 2018; Tomsett and Leyland, 2019). RS can help in understanding morphological trajectories because of new spatial and temporal resolution and detection capabilities (e.g. applications of hyperspectral imagery or green LiDAR). The capabilities and spatial extent of these techniques have grown considerably since the early 2000s. Piégay *et al.* (2015) highlighted a shift in the kind of tools used by geomorphologists to understand river systems. RS acquisition has partly informed the 'Great Acceleration' with data archives, so we can increasingly work within a BACI (before–after–control–impact) design (Green, 1979) based on robust hypothesis-driven protocols to assess changes and their drivers in comparative settings. When used alone, most field techniques only allow a short temporal perspective and access to a limited spatial context with no clear appraisal of processes occurring upstream or even laterally (notably in forested or large river systems). Integrative approaches, where field data, archived documentation (i.e. aerial photos, maps, topographic surveys) and remotely sensed information (which can be programmed, planned, repeated and archived) are combined allow fluvial geomorphologists to widen their spatial and temporal perspectives. RS sensors are now largely employed by river scientists in the field (e.g. terrestrial laser scan; aerial photos from drones; ground cameras) and RS data validation is usually based on intensive
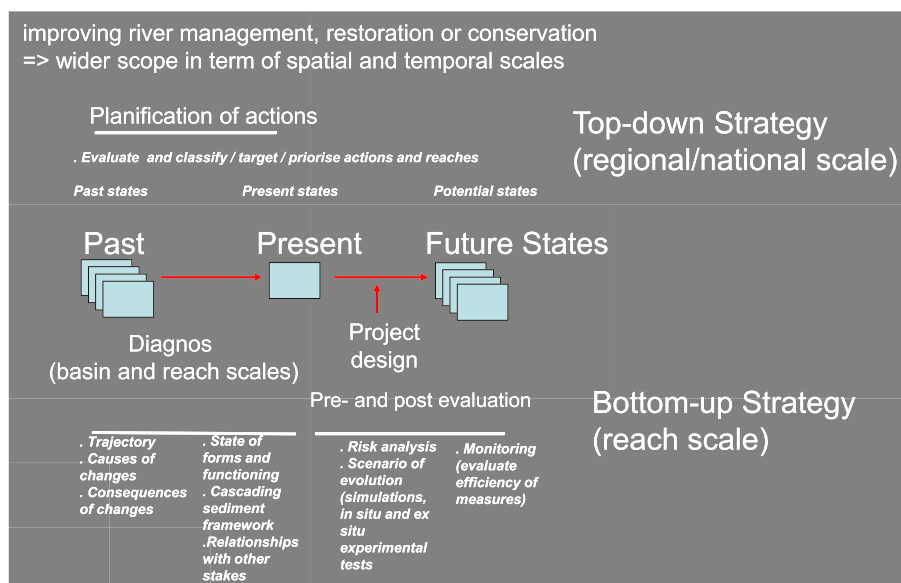

Figure 1.   General framework of geomorphic studies: diagnosis and project appraisal, top-down and bottom-up strategies. (From Piégay *et al.*, 2016, ch. 22.) [Colour figure can be viewed at wileyonlinelibrary.com]

field surveys (see Carbonneau and Piégay, 2012; Bizzi et al., 2016). In summary, RS offers new opportunities based on: (i) greater temporal resolution (i.e. repeated snapshots of the targeted landscape); (ii) larger spatial extents; (iii) higher spatial resolution; and (iv) use of contactless or non-invasive techniques (i.e. not disturbing the landscape).

Gilvear and Bryant (2016) in their review of the application of RS in fluvial geomorphology highlighted that RS is often the only way to obtain an 'overall picture' of river functioning at large scales. This overall picture is fundamental to understanding channel behaviour and changes, especially for the purposes of river planning and management frameworks, as highlighted for instance in Europe by the Water Framework Directive. Even if existing management-oriented frameworks are still mainly based on the acquisition of a large amount of local in situ data and require specific expertise of the river catchments to derive large-scale interpretations, they recognize the value and encourage the use of data and methods from RS.

Societies are shaping and modifying the landscape to a degree that has never occurred in the past. One of the key challenges for understanding remotely sensed rivers in the Anthropocene is to use the new, rapidly evolving technologies which provide an unprecedented ability to observe and understand the landscape. With this perspective in mind, we review research that investigates past, present and future fluvial conditions and processes, and summarize insights and challenges for new research.

Remote Sensing to Explore Past Conditions Within the Anthropocene

Data and methodological framework to diagnose river changes

Aerial photography
Reconstructing river trajectories requires the use of historical data, and especially RS information (Grabowski and Gurnell, 2016). Early studies mostly relied on the use of oblique and vertical aerial photography in the visible domain. The use of RS to explore past conditions starts with the advent of aerial photography around the 1930s, with mainly black and white images before the 1970s (Gilvear and Bryant, 2016). In many European countries, national aerial surveys were conducted with decadal frequency or even less from the 1950s (e.g. the historical archives of the French Geographical Institute: https://remonterletemps.ign.fr/).

Given the relatively coarse spatial resolution of early civilian airborne RS data (typically from 5 to 0.5 m), the smallest spatial scale that can be characterized over time corresponds to river features (e.g. changes in flow channel areas, emerged bare ground units, islands or riparian vegetation; Toone et al., 2014; Lallias-Tacon et al., 2017). The 2D reconstruction of channel planform dynamics from historical aerial photographs, sometimes combined with historical maps, has largely improved our understanding of channel metamorphosis (sensu Schumm, 1969), meander migration and channel shifting (Hooke, 2003; Alber and Piégay, 2017). Early studies (e.g. Petts et al., 1989; Gurnell et al., 1994; Hooke, 2003) focused on 2D interpretation but did not quantify geomorphic work or sediment volumes, which limited the understanding of channel response. Historical aerial photographs have been used to detect channel changes in recent decades (e.g. Liébault and Piégay, 2002; Kondolf et al., 2007; Surian et al., 2009; Comiti et al., 2011; Arnaud et al., 2015; Marchese et al., 2017) to corroborate conclusions derived from traditional field-survey methods;

to understand the causes of channel changes (Rollet et al., 2013; Grabowski and Gurnell, 2016; Bizzi et al., 2019); and to isolate human impacts on rivers since the 1950s, especially since the 'Great Acceleration' of impacts in the Anthropocene era (Brown et al., 2017).

Satellites
Historical analyses of changing river systems now also use satellite products. Landsat Thematic Mapper (TM) multi-spectral data at 30 m resolution covers a temporal extent of 30 years (http://landsat.usgs.gov) but this is still limited to main river branches (Donchyts et al., 2016). Dewan et al. (2017) assessed channel changes of the Ganges–Padma River over 200 km and 38 years, and found significant channel shifting over the 1973–2011 period related to changes in the hydrological regime but no real geomorphic changes, which may be attributed to upstream dams. Pekel et al. (2016) quantified changes in surface freshwater globally using the entire Landsat 5, 7 and 8 archives over the past 32 years (1984–2015; ~3 million images). An increasing number of papers have recently been published on channel changes based on such Landsat archives because the images are free of charge and the temporal range is now sufficient to detect channel response to specific drivers (mainly damming), in the case of responsive rivers.

Satellite images are becoming increasingly available with a resolution allowing users to explore smaller riverine systems globally. However, with the exception of Landsat, the temporal window covered by satellite data is still too short for historical analysis. Satellite imagery is therefore accurate to characterize processes at an inter- and intra-annual scale, but not yet for detecting channel changes over decades beyond last 30–40 years. For longer channel temporal trajectories, or smaller rivers, satellite records are insufficient. Data can be supplemented by historical map data to extend data records, as used by Ricaurte et al. (2012) to compare the contemporary and historical distribution of vegetated islands in sections of the Danube, Rhine and Olt rivers.

Complementary field data
RS data can be complemented with more traditional field approaches to increase the set of convergent evidence confirming changes in channel morphology and their drivers. Historical hydrometric archives of stream gauging stations are commonly used to quantify long-term changes in channel width, depth and riverbed elevation, and to understand the driving processes (James, 1999; Stover and Montgomery, 2001; Slater and Singer, 2013; Phillips and Jerolmack, 2016; Pfeiffer and Finnegan, 2018). Long profiles are also available at regional or national scales, sometimes with historical resources (Liébault et al., 2013). Additionally, time series of discharge and stage can be used conjointly to estimate changes in channel depth and conveyance (e.g. Biedenharn and Watson, 1997; Pinter and Heine, 2005). Finally, hydrometric data are increasingly being used to quantify the influence of changes in channel conveyance on flood frequency (Slater et al., 2015).

Reach-scale changes

Classical approach from airborne images
A classic approach to analyse reach-scale channel adjustments over multiple kilometres is to compile historical aerial photographs. Series of photographs are selected at least every 10 years, depending on the availability of archived photos and flood dates, and integrated in a geographic information system (GIS) environment to extract geomorphic variables, e.g. active channel width or sinuosity, gravel bar area (Gilvear et al.,

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Earth Surf. Process. Landforms, Vol. 45, 157–188 (2020)

2000; Ollero, 2010; Michalková *et al.*, 2011; Rollet *et al.*, 2013; Toone *et al.*, 2014; Arnaud *et al.*, 2015; Lallias-Tacon *et al.*, 2017; Scorpio *et al.*, 2018) and landscape unit characteristics (e.g. Dufour *et al.*, 2015; Solins *et al.*, 2018). Image georeferencing and vectorization of river features from historical datasets are still mostly manual and time-consuming tasks which require real expertise. By analysing the temporal series of historical RS data, we can detect discontinuities in the spatiotemporal trajectories of rivers. Homogeneous sub-reaches in terms of magnitude of change can be statistically delineated using tests for stationarity (Alber and Piégay, 2011; Roux *et al.*, 2015). Aerial photographs are also broadly used to study patterns of pioneer and woody riparian vegetation related to regional/climatic factors and human disturbance, and link these changes with river pattern changes to assess vegetation controls (Aguiar and Ferreira, 2005; Dufour *et al.*, 2007; Kondolf *et al.*, 2007; Cadol *et al.*, 2011; Dufour *et al.*, 2012; Belletti *et al.*, 2015; Surian *et al.*, 2015; Kui *et al.*, 2017; Safran *et al.*, 2017). Dépret *et al.* (2017) and Tena *et al.* (2019)

analysed a set of aerial photographs from different sites of the Rhône River and underlined effects of channel regulation on cutoff channel life span and groyne field terrestrialization (Figure 2A). Decadal changes in species composition and landscape configuration can also be surveyed with satellite images (Rodríguez-González *et al.*, 2017).

Added value of combining field and airborne data
Archived aerial photos and field surveys can be used jointly to assess both planform and vertical channel changes or vegetation properties. For example, Arnaud *et al.* (2015) exploited seven sets of aerial photos and three cross-section series from the 1950s to the 2010s to quantify channel narrowing/widening and bed degradation/flood terrace aggradation rates on the dammed Rhine River. Belletti *et al.* (2014) assessed the influence of floods on riverscape organization of 12 braided reaches (French Rhône basin) by using five archived aerial photos series and sediment regime information from archived longitudinal profiles (Liébault *et al.*, 2013). Sequences
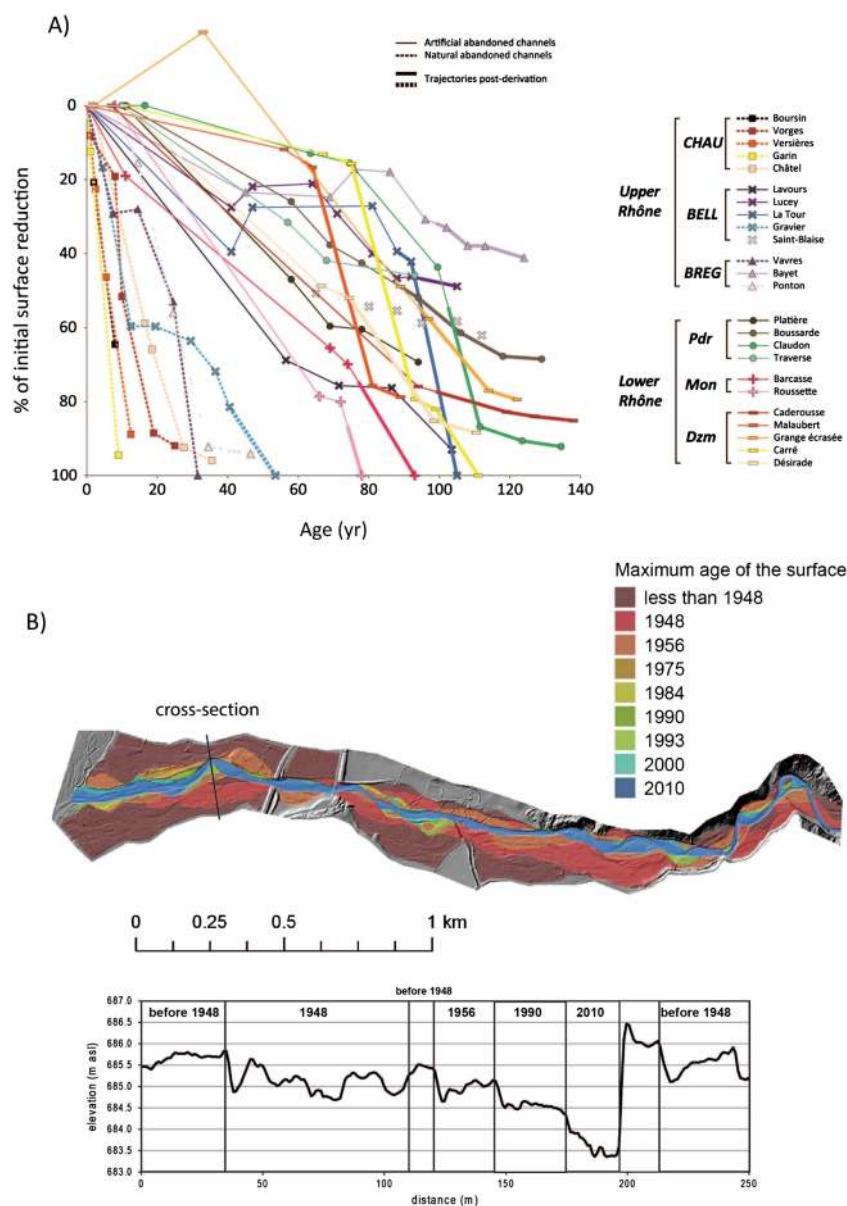

Figure 2. Temporal evolution of surface areas through time based on a series of aerial photographs. (A) Example of the terrestrialization of the natural (dashed line) and artificial (thick line) abandoned channels of the Rhône River – Grange Ecrasée is the only case of expansion right after cut-off and then shrinking (from Dépret *et al.*, 2017). (B) Reconstruction of bed-level evolution of a small alpine gravel-bed stream from the combination of historical aerial photographs (from 1948 to 2010) and a recent airborne LiDAR survey (2010) (modified after Lallias-Tacon *et al.*, 2017); historical aerial photographs have been used to date recent terraces, and airborne LiDAR data to extract elevation differences between dated terraces to reconstruct the floodplain formation history. [Colour figure can be viewed at wileyonlinelibrary.com]

of archive images and field measures of standing tree volumes have been also used to determine wood recruitment through time and contribute to wood budgeting (Lassettre *et al.*, 2008; Boivin *et al.*, 2017). With the emergence of new RS technologies, it is now much easier to combine sequences of archive imagery with topographic information, and to move a step forward towards the reconstruction of 3D multi-decadal channel responses. For instance, sequential aerial photos since the 1940s–1950s and present-day LiDAR data were combined to reconstruct floodplain formation and relate this to vegetation properties along three alpine braided rivers in France (Figure 2B; Lallias-Tacon *et al.*, 2017). RS has also been used to estimate riverbank erosion volumes for different river reaches in New Zealand (Spiekermann *et al.*, 2017).

The time periods covered by national aerial photograph series are typically too short to explore lowland rivers that are less responsive to change. In these larger river systems, RS data must be combined with other data such as sedimentological information from coring or geophysics to access information ranging from the medieval period to the 20th century (Vauclin *et al.*, 2020).

Vertical information can also be derived directly from archived aerial photographs using digital photogrammetry (Lane, 2000; Gilvear and Bryant, 2016; Bakker and Lane, 2017). For example, Carley *et al.* (2012) assess post-dam channel changes by combining elevation contour maps acquired from aerial photogrammetry, *in situ* bathymetric surveys and point cloud models acquired from a total station. On the other hand, geomorphic metrics extracted from archived aerial photographs or 3D bed topography offer input/validation data for linking hydraulic modelling with channel change (Santos *et al.*, 2011; Gilvear and Bryant, 2016; Serlet *et al.*, 2018). However, extracting channel change information from archived data (e.g. old aerial photographs) is not straightforward and requires an assessment of error production and propagation to allow its application for quantitative geomorphic analysis (James *et al.*, 2012; Bakker and Lane, 2017). For example, it has been demonstrated that structure-from-motion (SfM) data processing of historical aerial photos of braided channels can produce a quality of information equivalent to classical photogrammetric approaches, provided that image texture and overlap are sufficiently high for tie-point detection and matching (Bakker and Lane, 2017). However, the persistence of systematic centimetre- to decimetre-scale elevation errors after coregistration of point clouds indicates that topographic differencing using SfM processing of archival imagery is still limited for the quantitative analysis of sediment budgets.

The integration of large-scale historical data (beyond RS) is often used to better contextualize reach-scale changes within a catchment and landscape context. For example, Ziliani and Surian (2016) combine catchment-scale datasets on river pressures (e.g. bank protection, sediment mining, chronology and location of torrential control works), RS-derived information (land use changes), historical maps and aerial photos to disentangle the contribution of local versus large-scale drivers in the evolutionary trajectory of channel morphology along the nearly-natural Tagliamento River (northwestern Italy).

Regional network changes

Reach-scale river trajectory assessment, combining field data, manual editing of historical remotely sensed information and qualitative expert-based interpretation of process evidence, is a research challenge that requires careful harmonization and consistency when implemented at regional or network scales (several thousands of kilometres of river length). Two strategies

are usually implemented: (i) assessing inter-reach differences at the network scale to infer controlling factors; and (ii) observing continuous network changes.

Assessing inter-reach differences at the network scale to identify controlling factors

Past evolutionary trajectories can be explained, and future trajectories can sometimes be predicted, through *location-for-time* substitution, which infers a temporal trend from a study of different aged sites, permitting regional assessment of channel changes (Pickett, 1989; Fryirs *et al.*, 2012) or *location-for-condition* evaluation allowing to identify factors explaining observed changes. This location-for-time approach builds on the well-known channel-evolution model of Schumm *et al.* (1984) and Simon and Hupp (1986). Such historical large-scale studies are usually based on relatively few observations (at best decadal), mainly aerial photos (e.g. Belletti *et al.*, 2014), manually digitized historical maps (Scorpio *et al.*, 2016; Meybeck and Lestel, 2017) or a combination of aerial photos and maps (e.g. Surian *et al.*, 2009). Regional active corridor changes are estimated through location-for-condition evaluation by sampling a set of river reaches or river features within a hydrographic network that can be compared in space and time (Belletti *et al.*, 2015). The approach mainly consists in combining present RS data and spatially distributed historical information within a catchment to interpret controls of present channel conditions. Belletti *et al.* (2015) explored active channel width evolution between the 1950s and 2000s in French braided rivers that showed general narrowing in the northern reaches versus more complex patterns in the southern reaches. Applying the location-for-condition evaluation, Bertrand and Liébault (2019) studied the impact of nickel-mining activities on the river beds in New Caledonia by comparing the spatial patterns of present active channel width normalized by the catchment area in a set of undisturbed versus impacted reaches, identified on recent orthophotos. They demonstrated that the increase in coarse sediment supply induced sediment waves that propagated from the major mining sources, widening and aggrading active channels along the stream network. An advanced approach in this domain by Liébault *et al.* (2002) showed from co-inertia analysis that differences in channel changes in 20 mountain streams (channel narrowing, bed degradation and armouring) were largely controlled by watershed morphometry and land use, permitting a better understanding of sub-catchment sensitivity to change. Recently, Alber and Piégay (2017) predicted potential bank retreat at an entire network scale from stream power and active channel width based on a set of sites/observations where bank retreat was assessed over a 50-year period from two series of aerial photos.

Observing continuous network changes

This second approach has become possible in the last 10 years thanks to a better temporal and spatial resolution in RS data. It relies on the integration of optical, multi-spectral (orthophotos or satellite images) and topographic (LiDAR) data. Macfarlane *et al.* (2017) combined Landsat imagery and a modelled estimate of pre-European settlement land cover, and showed, over 50 000 km of rivers, that 62% of Utah rivers and 48% of the Columbia River Basin network exhibited significant differences in riparian vegetation compared to historic conditions due to land-use impacts and flow and disturbance regime changes. Bizzi *et al.* (2019) derived in the Piedmont river network (Italy) historical and current hydraulic scaling laws by integrating a recent regional geomorphic database based on remotely sensed datasets (Demarchi *et al.*, 2017), sparse historical field measurements of channel cross-sections, and evidence from unaltered river systems in similar Alpine regions in France
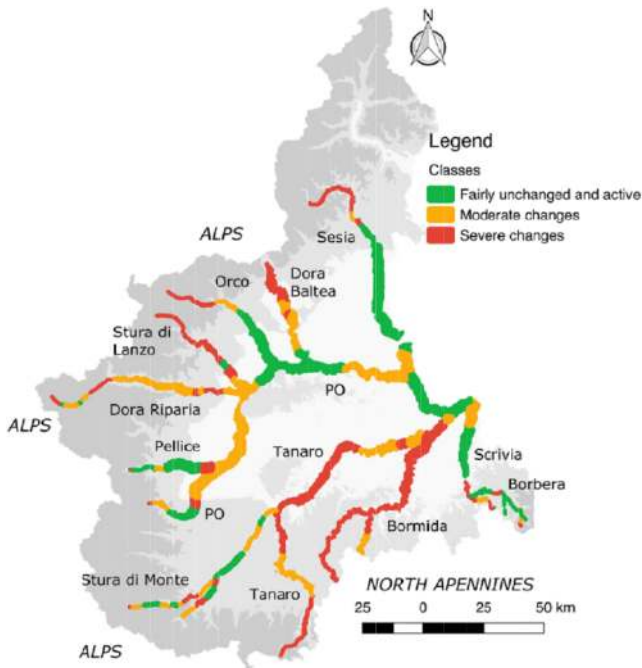
Figure 3. Classes of channel changes combining incision and narrowing based on regional LiDAR, aerial photos and field/archived data to established reference: severe changes indicate significant narrowing (>50–100% of their current width) and riverbed incision (2–5 m) over the last century; moderate changes indicate mostly river reaches that show substantial narrowing and moderate channel incision. (From Bizzi *et al.*, 2019) [Colour figure can be viewed at wileyonlinelibrary.com]

(Figure 3) (Piégay *et al.*, 2006; Gob *et al.*, 2014). It has long been recognized that past changes in channel characteristics can be used to predict long-term trajectories of channel morphology. Comparing these relationships with present channel measurements provides an indication of the level of channel modification at the regional scale due to human pressures over the last century. Such approaches are promising for understanding river evolution over much larger scales in the future.

Historical maps are rare and not so widely used as additional layers to quantify temporal changes at a regional level because of limitations (geometric distortion, simplified representation of features, notably the hydrography) (Dunesme *et al.*, 2018). But there are some opportunities in countries such as Switzerland or Belgium that have very good historical map resources covering the 19th century and for which automatic vectorization is possible (Horacio *et al.*, n.d.).

Remote Sensing to Identify Patterns and Acting Processes

Characterizing rivers from ground, sky and space

Remotely sensed approaches of river systems can be classified according to the scale of observation, ranging from ground-based and close-range surveying techniques to airborne and spaceborne platforms (Table I).

Ground-based and close-range surveying techniques
Field-based approaches in fluvial geomorphology increasingly use terrestrial RS to survey the topography and to measure the fluxes of water, sediment or wood passing through a river section. For example, TLS is now commonly employed to produce

dense 3D point clouds of river channels (e.g. Milan *et al.*, 2007; Heritage and Milan, 2009; Hodge *et al.*, 2009). Although this technique is mostly used at scales ranging from small gravel patches to short channel reaches of several hundreds of metres, combining TLS with mobile platforms allows for coverage of several kilometres of non-wetted area in complex river channels (Williams *et al.*, 2014). Time-lapse cameras (Džubáková *et al.*, 2015), video recordings (Le Coz *et al.*, 2010; MacVicar and Piégay, 2012), seismic sensors (Burtin *et al.*, 2016) or active radio frequency identification (RFID) tracers (Cassel *et al.*, 2017) are now in the modern toolkit for the ground-based observation of fluvial forms and processes. The main limitation of ground-based observations remains the small spatial coverage of investigation.

Airborne techniques
Airborne surveys can be made using a range of platforms, from the most affordable and flexible ones (poles, lighter-than-air balloons or blimps, small unmanned aerial vehicles (UAVs) also called unmanned aerial systems (UAS)) to manned aircraft (ultralight trikes, helicopters, planes) (Figure 4). Blimps (Vericat *et al.*, 2009; Fonstad *et al.*, 2013) and poles (Bird *et al.*, 2010) used to obtain high-resolution images in short river reaches, typically less than 1 km in length, are particularly appropriate in narrow river channels partially or totally masked by forest canopy. UAVs can more easily cover several kilometres of wide river reaches (e.g. Woodget *et al.*, 2015; Vázquez-Tarrío *et al.*, 2017). Airborne observations allow for the investigation of larger spatial scales with constraints of flight duration, optical properties of the sensor and flying height of the platform. In co-evolution with UAV and ultralight trikes, SfM photogrammetry has largely resolved the issue of image orthorectification and digital elevation model (DEM) production (James and Robson, 2012; Westoby *et al.*, 2012; Fonstad *et al.*, 2013). Such low-cost platforms are usually equipped with commercial digital cameras, with varied configurations and technical options as technology is rapidly evolving (Marcus and Fonstad, 2010; Bertoldi *et al.*, 2012; MacVicar *et al.*, 2012; Entwistle *et al.*, 2018). More recently, there is a growing availability of drones equipped with real-time kinematic (RTK) GPS allowing for centimetre accuracy positioning of the imagery. The popular Phantom series of drones produced by DJI Inc. now has a model equipped with such RTK-GPS technology and the cost is of approximately 7000 euros (in early 2019). This technical development should further enhance the ease of use of UAVs for geomorphological investigations. As a consequence of these key technological advances, published papers on the use of UAVs in river settings have appeared at an accelerated pace with a Google Scholar search for keywords 'UAV River' returning over 9000 items published since 2015. Drones are now equipped with LiDAR sensors, multi- and hyper-spectral sensors and even RFID tracking technology (Cassel *et al.*, 2019).

However, we note that this rapid growth of technologies with increasing levels of automation has not been without negative effects. In the case of SfM photogrammetry, the major drawback of the high levels of automation has in fact been a net loss, or at the very least a stagnation in growth, of photogrammetric expertise in the geomorphology community. Modern softcopy SfM photogrammetry packages will often deliver visually stunning results and extremely high data volumes irrespective of the quality of the input data. Since it is increasingly difficult to validate a significant percentage of these outputs with field data, they are too often accepted as good without detailed examination. After the appearance of the first papers on the topic of SfM in 2012/2013, it has taken several years and multiple contributions to recognize that SfM photogrammetry, while still strongly rooted in photogrammetry, requires its own expertise. The best

Table I. A few examples of corridor features and attributes remotely sensed from a set of platforms/sensors within specific space–time frameworks

Riverscape features and attributes	Ground	UAV/UAS/ Ultralight	Plane/ helicopter	Satellite	Spatial coverage	Multitemporal survey	Type of data sensed	References
Grain characters								
Grain size	X				1 m²	No	TLS	Hodge et al. (2009)
	X				180 m²	No	TLS	Heritage and Milan (2009)
	X				Flume and field sampling (~1 m²)	No	Ground photos	Stähly et al. (2017)
	X				0.5 m²	No	Ground photos	Purinton and Bookhagen (2019)
		X			2.5 km	Yes	Aerial photos (RGB)	Vázquez-Tarrio et al. (2017)
		X			Reach scale	No	UAV/SfM	Carbonneau et al. (2018)
			X			No	Ground photos, airborne LiDAR	Chardon et al. (2019)
Grain shape	X				Reach and catchment scale	No	Ground photos	Litty and Schlunegger (2016)
Grain roundness	X				Catchment scale	No	Ground photos	Roussillon et al. (2009)
	X				Gravel bar	No	TLS	Hayakawa and Oguchi (2005)
	X				Catchment scale	No	Ground photos	Cassel et al. (2018)
Channel characters								
Geomorphic features		X			Javoří brook (1 km-long stretch, catchment: 11 km²)	No	Aerial photos (RGB)	Langhammer and Vacková (2018)
			X			No	Airborne LiDAR	Wheaton et al. (2015)
			X		Drôme network (1640 km²)	No	Orthophotos (RGB and NIR)	Bertrand et al. (2013a)
			X		Piemont region (1200 km of rivers).	No	Aerial photos (with multispectral information, RGB and NIR), low-resolution airborne LiDAR	Demarchi et al. (2017)
			X		Set of reaches (n = 53) – regional network	Yes	Aerial orthophotos and historic aerial photos, high-resolution (<1 m)	Belletti et al. (2015)
				X	All Red River Basin (21 000 km of rivers), Vietnam	No	Google Earth (based on Digital Globe Quikbird and CNES Spot Image), topographic data (ASTER V2 GDEM), discharge data and sediment rating curve	Schmitt et al. (2014)
Instream wood size and distribution		X			Several river reaches along the Blanco River	No	UAV/SfM with an RGB camera	Sanhueza et al. (2018)
			X		River reach	No	Airborne LiDAR	Atha and Dietrich (2016)
			X		Lamar River and the Cooke City Reach of Soda Butte Creek	No	Airborne hyperspectral imagery	Marcus et al. (2002, 2003)
				X	146 river reaches along the Queets River	No	Google Earth imagery	Atha (2014)
Instream wood volume		X			6 river reaches along the Clear Creek	No	UAV-SfM with an RGB camera	Truksa (2017)
			X		River reach	No	Airborne LiDAR	Atha and Dietrich (2016)
				X	10 km along the Blanco River	Yes	Digital Globe satellite imagery and three-band imagery derived from an airborne LiDAR survey	Ulloa et al. (2015)

(Continues)

Table 1. (Continued)

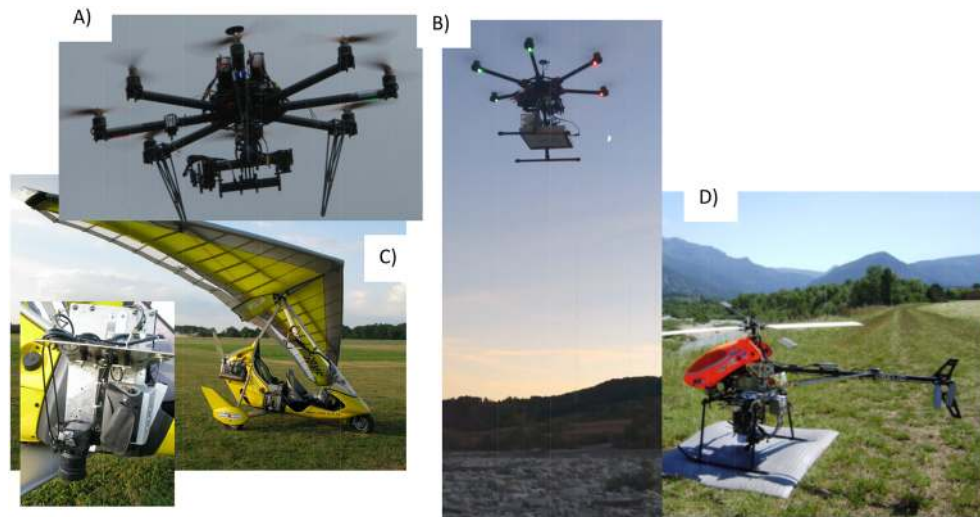| Riverscape features and attributes	Ground	UAV/UAS/Ultralight	Plane/helicopter	Satellite	Spatial coverage	Multitemporal survey	Type of data sensed	References
		X			Several reaches along the Blanco River	No	UAV/SfM with an RGB camera	Sanhueza et al. (2018)
	X				14 ha of the Piave River	No	TLS	Tonon et al. (2014)
		X			River reach Kuzlovec Torrent	No	TLS	Grigillo et al. (2015)
Topography (excluding bathymetry)	X				Proglacial fan of Glacier du Mont Miné and Ferpècle, Swiss Alps (5800 m²)	Yes	TLS	Milan et al. (2007)
			X		Bès River, 7 km	Yes	Airborne LiDAR	Lallias-Tacon et al. (2014)
Topography (including bathymetry)	X		X		Rees River, 2.5 km	No	TLS and aerial photos (RGB)	Williams et al. (2014)
		X			Elbow River, 1 km	No	Aerial photos (RGB)	Tamminga et al. (2015)
		X			White River, 0.25 km	No	Aerial photos (RGB)	Dietrich (2017)
			X		Waimakariri River, 3.3 km	Yes	Airborne LiDAR and aerial photos (RGB)	Lane et al. (2003)
			X		2 reaches on Soda Butte Creek, 0.385 km and 0. 440 km	Yes	Airborne LiDAR and aerial photos (RGB)	Legleiter (2012)
			X		Pielach River, 1–2 km	Yes	Green airborne LiDAR	Mandlburger et al. (2015)
			X		Ste-Marguerite River, 80 km	No	RGB camera	Carbonneau et al. (2006)
Water, sediment and wood fluxes								
Water level		X			Ridracoli reservoir	Yes	UAV with an RGB camera	Ridolfi and Manciola (2018)
				X	Ganges and Brahmaputra rivers	Yes	AMSR-E and TRMM sensor	Hirpa et al. (2013)
Flow velocity	X				River reach	No	Home movies from YouTube and LSPIV	Le Boursicaud et al. (2016)
	X				Laboratory small-scale experiments and field sites on La Morge River at Voiron (<1 km²)	Yes	Ground camera images (B&W)	Jodeau et al. (2017)
	X				Yufeng Creek (cross-section width of 15–30 m)	Yes	Ground camera images (RGB)	Huang et al. (2018)
		X			River reach	No	UAV and the Kande–Lucas–Tomasi (KLT) algorithm	Perks et al. (2016)
Pebble mobility	X				2.3 km	Yes	Passive RFID tags	Liébault et al. (2012)
		X			22 ha, Büech River	No	Active RFID antenna mounted on a drone	Cassel et al. (2019)
Instream wood flux	X				River reach along the Ain River	Yes	Video camera	MacVicar and Piégay (2012)
	X				River reach	Yes	Time-lapse photography	Kramer and Wohl (2014)
	X				Génissiat reservoir on the Rhône River (section about 0.35 km²)	Yes	Ground images (RGB)	Benacchio et al. (2017)
			X	X	River reach along the Saint-Jean River	Yes	Aerial and satellite imagery	Boivin et al. (2017)
	X				27 rivers reaches	Yes	Home movies from YouTube	Ruiz-Villanueva et al. (2019)

Figure 4. Example of platforms used by scientific teams to acquire hyperspatial imagery: (A) octocopter; (B) hexacopter equipped with an active RFID antenna; (C) ultralight trike equipped with RGB and thermal cameras; (D) unmanned control helicopter. (Sources: A, Franck Perret; B, Mathieu Cassel; C, Baptiste Marteau; and D, Kristell Michel.) [Colour figure can be viewed at wileyonlinelibrary.com]

example is the debate around optimal flight patterns and camera calibrations. Given that nadir image acquisition had been the norm in the first 50 years of photogrammetry, SfM photogrammetry acquisitions initially employed this approach. But some early papers (Wrackow and Chandler 2008, 2011; James and Robson 2014; Woodget *et al.*, 2015) started to document a doming deformation whereby the centre of a digital elevation model produced with SfM photogrammetry was either depressed or elevated along a parabolic shape. The simulation work of James and Robson (2014) and laboratory experiments of Wrachow and Chandler (2011) further demonstrated that this doming deformation was due to poor camera calibration due to the exclusive use of nadir imagery. It is now well recognized that for SfM photogrammetry with low-cost cameras the acquisition of off-nadir imagery with convergent views is critical. Significant photogrammetric expertise is required to correctly adapt SfM technology to a geomorphic context. This is also true for hardware. UAV-based LiDAR systems are now increasingly common; however, anecdotal evidence (Lejot, pers. comm.) suggests that getting these systems to an operational state is not straightforward. Once again, very significant technical expertise is required. Overall, airborne acquisition technology has advanced considerably, but potential users must be aware that significant expertise and time are still critical requirements for successful deployment of these technologies.

Spaceborne techniques

For working at larger spatial scales, satellite images are also becoming an important source of data. Since the advent of multispectral satellite images (around the late 1970s for the Landsat TM), satellites have provided access to further information derived from electromagnetic radiation that is complementary to field-based data or aerial photographs, mainly for large rivers (e.g. Salo *et al.*, 1986; Henshaw *et al.*, 2013). Landsat 7 and 8 with images at 15 and 30 m resolution and a revisit capacity of 16 days are often used at large scales, e.g. for characterizing thermal patterns (Wawrzyniak *et al.*, 2016) or channel morphology (Xie *et al.*, 2018). Early work using Landsat 5 images focused on channel migration in the Peruvian Amazon (Salo *et al.*, 1986). The main advantage is that these images are globally available and free of charge to users. If metric-scale resolutions are required, commercial satellite products become the only option. SPOT 5 imagery has been used associated with LiDAR and very-high-resolution (VHR) QuickBird images to map riparian zone features (Johansen *et al.*, 2010). Since 2015,

SPOT 6 and 7 programs now offer daily images at 1.5 m in panchromatic mode. The Pleiades program (launched in 2011–2012) produces daily images at 70 cm resampled at 50 cm, which have been used to map aquatic areas in river corridors and assess their spatial extent according to discharge (Wawrzyniak *et al.*, 2014). These data sources provide VHR images but the acquisition costs can be particularly high for large-scale or multitemporal studies. In recent years, there has been an increase in the number of studies using Sentinel images in visible, infrared and radar domains (e.g. Spada *et al.*, 2018, who combine data from the CORONA, Landsat and Sentinel 2 missions), which are publicly accessible and provide high spatial resolution (10–60 m) images in Europe every 5 days (if no cloud), or weekly or sub-monthly, at the global scale.

Over the past few decades, geomorphologists have advocated for an increase in spatial resolution, whereas now some of the geomorphic questions are solved when resolution is reduced (e.g. channel bathymetry from radiometric information). An issue is then to determine the optimal resolution and level of change detection for solving geomorphic questions.

In recent years, satellites have increased in spatial resolution (reaching sub-meter scales) and frequency of acquisition (subweekly acquisition), collecting multispectral and radar information and in some cases (such as Pleiades) stereoscopic datasets for topographic/DEM reconstruction. We are entering an era where river channel planforms and processes can be observed and classified from satellites almost weekly for large rivers worldwide. This opportunity requires specific and interdisciplinary expertise as well as access to funding/resources to be properly realized. For this reason, this new satellite information has not yet produced a concrete advance in river process understanding. RS-derived information has so far mostly been used to test existing concepts and their range of applications, rather than for generating new concepts or theory. The time has come to translate our request for data (now partially satisfied) into efforts to use these data to pose specific research questions to advance fluvial geomorphology scientific understanding.

Detection and characterization of fluvial forms and their attributes

Grain size and shape measurement

The grain-size distribution (GSD) of river channels is critical for understanding the interactions between hydraulics, sediment

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Earth Surf. Process. Landforms, Vol. **45**, 157–188 (2020)

transport and channel form, and for the characterization of physical habitats. Investigations of the spatial variability of river sedimentology is at the core of many works dedicated to sediment sorting patterns and processes of fluvial environments (e.g. Dietrich *et al.*, 1989; Rice and Church, 1998; Guerit *et al.*, 2014). Collecting data about surficial GSD has, for a long time, only been possible through laborious and time-consuming field samplings, such as the well-known pebble count protocol (Wolman, 1954). Remotely sensed solutions started to emerge in the late 1970s, with the development of 'photo-sieving' image analysis tools. Initially, photosieving methods relied on manual measurement of clasts visible on images taken from the ground (e.g. Adams, 1979; Ibbeken and Schleyer, 1986). Later solutions became based on the automatic segmentation and size extraction of single particles on close-range images of gravel patches (Butler *et al.*, 2001; Graham *et al.*, 2005a, 2005b; Detert and Weitbrecht, 2012). At similar scales, other methods started to emerge which relied on statistical properties of images. Image-based sedimentological extraction initially used a grain-size calibration with image texture, semivariance or entropy (e.g. Carbonneau *et al.*, 2004; Tamminga *et al.*, 2015; Woodget *et al.*, 2018). Wavelet analysis and autocorrelation have also been demonstrated as being capable of extracting grain-size information from imagery (Rubin, 2004; Buscombe, 2008; Buscombe and Masselink, 2009; Buscombe *et al.*, 2010). Chardon *et al.* (2019) tested the automatic Buscombe procedure on underwater images and showed solar lighting conditions and particle petrography influence significantly the GSD. They proposed procedures to correct these effects and determine the optimal sampling area to accurately estimate the different grain size percentiles when using such a technique, which is still the only accurate approach to characterize grain size underwater. Similar approaches would later be applied to airborne data in order to extend the spatial coverage of remotely sensed grain size mapping approaches (Figure 5).

As an alternative, the 3D point cloud-based technique uses roughness metrics to approximate grain size (e.g. Heritage and Milan, 2009; Brasington *et al.*, 2012; Vázquez-Tarrío *et al.*, 2017). Only a few recent works proposed a comparison between these techniques. Woodget *et al.* (2018) tested a 2D image texture approach and a 3D topographic roughness approach in a small gravel-bed river in UK and obtained a better grain-size prediction with the 3D approach. However, another field experiment showed that the texture of single UAV images is more efficient than 3D roughness metrics for grain-size prediction, provided that UAV images are acquired with a mechanical stabilization system (gimbal) to avoid a blurring effect (Woodget *et al.*, 2018). First attempts to predict grain size with 3D point clouds were based on local standard deviation of elevations, which were determined by scale-dependent submeter kernels (Entwistle and Fuller, 2009; Heritage and Milan, 2009). More recent works demonstrated that detrending the local micro-topography (e.g. bank slope, edges of gravel bars) before computing the roughness metrics is crucial for grain-size prediction (Brasington *et al.*, 2012; Rychov *et al.*, 2012; Vázquez-Tarrío *et al.*, 2017).

Recently, Carbonneau *et al.* (2018) demonstrated a method that leverages direct georeferencing (DG) in order to roboticize the grain-size mapping process. By using the on-board GPS of a drone, and by flying at very low altitudes (below 10 m), the authors demonstrated that drone images could be combined in a DG workflow that uses particle recognition software. As a result, the method of Carbonneau *et al.* (2018) allows a drone to act as a fully autonomous robotic field worker that measures grain-size data over local areas. With the advent of hyperspatial RS solutions at larger scales, grain-scale information can now cover entire river reaches of several kilometres in length. The airborne LiDAR topographic survey can also accurately generate grain-size maps when the point density is high (38–49 points m^{-2}, mean distance between points of 0.08–0.09 m) and the laser spot size fairly low (0.12 m at NADIR; see Chardon *et al.*, 2019), comparative to observed grain sizes, allowing areas much larger than with drones to be covered.

The study of longitudinal grain shape evolution helps in understanding the downstream fining and rounding processes and enhances our ability to decipher the transport history of river sediment (Domokos *et al.*, 2014; Litty and Schlunegger, 2016) and interpret gravel provenance (Lindsey *et al.*, 2007) (Figure 6). From traditional field measures which emerged in the 1930s (Wadell, 1932), image processing and Fourier grain shape analysis were used in the 1990s in the first attempts to automatically measure particle shape and roundness (Diepenbroek *et al.*, 1992). This approach was further developed in the late 2000s using automatic ground imagery procedures to obtain a set of roundness and shape indexes and explore spatial patterns at reach to network scales (Roussillon *et al.*, 2009; Cassel *et al.*, 2018). A digital approach has also been proposed to estimate roundness of individual particles using a 3D laser scanner, but it is still at an experimental level, without *in situ* results (Hayakawa and Oguchi, 2005). Using a large set of SfM field data, Pearson *et al.* (2017) highlighted effects of particle shape or grain packing structure on roughness/grain-size relationships, opening new issues to potentially characterize particle shape from
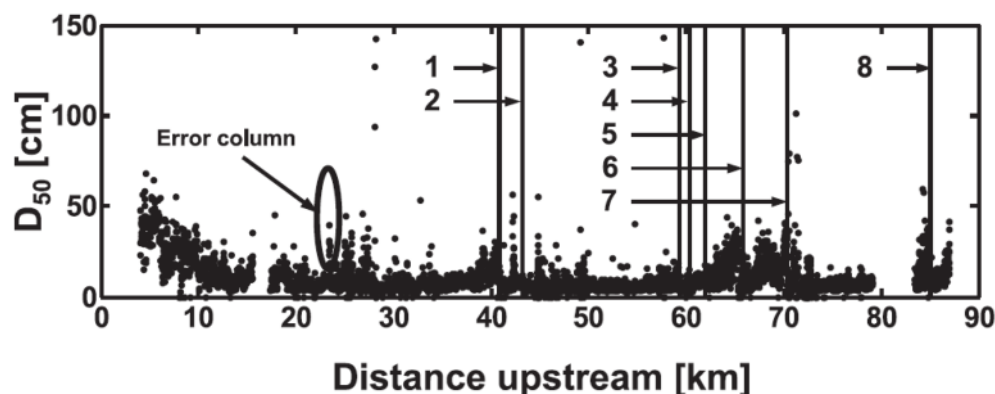

Figure 5. Long profile of median grain size over 80 km of the Sainte Marguerite River, Québec, from image processing and showing link cutoff points (vertical lines), numbered 1–8 as determined by Davey and Lapointe (unpublished report, 2004) and an example of an 'error column' structure caused by glare at the water surface. (From Carbonneau *et al.*, 2005.)
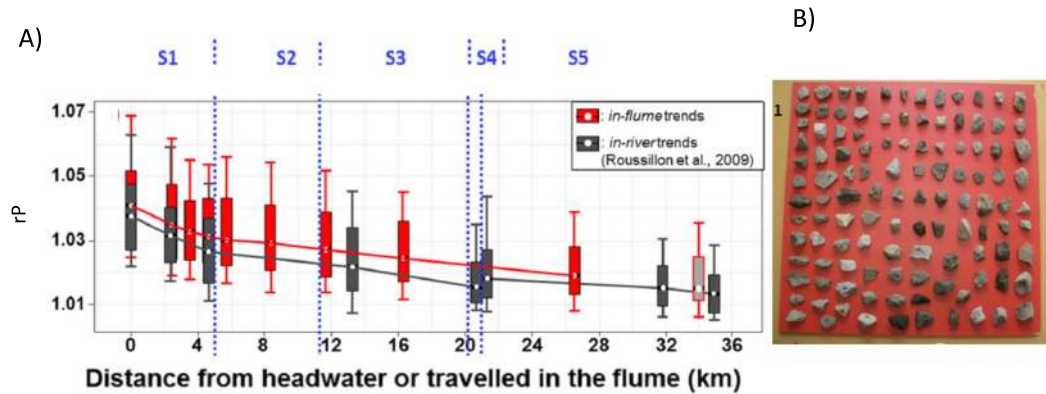
Figure 6. (A) Evolution of the ratios of perimeters rP according to the distance travelled through 36 km from the headwater of Progo River (Indonesia) (dark grey) or in an annular flume (red). rP = Pg/Pe, with Pg the pebble perimeter and Pe the ellipse perimeter, both having the same surface area. The single clear grey boxplot with red borders represents value distributions of rounded pebbles which were collected 30 km downstream the Progo spring. Boxplots represent distributions of shape parameter values at a given distance and provide 10th, 25th, 50th, 75th and 90th percentile values. White circles represent median values. (B) Example of picture of angular pebbles taken for roundness analysis. (Modified from Cassel *et al.*, 2018.) [Colour figure can be viewed at wileyonlinelibrary.com]

imagery without sampling particles and disrupting the bed surface. However, particle roundness characterization needs an accurate detection of particle boundaries; therefore such measurement is still difficult to imagine without field sampling.

Bathymetry and water depth

Water depth is arguably the most fundamental parameter in fluvial morphology and has been the topic of considerable work in fluvial RS. We can distinguish three main approaches to water depth mapping: radiometric depth retrieval, direct measurement with photogrammetry and active measurements with bathymetric LiDAR. Radiometric depth retrieval uses the Beer–Lambert law of absorption and correlates the brightness levels in an image with the depth of water. Crucially, the bottom of the river must be clearly visible. This empirical approach has been frequently used and reported (Winterbottom and Gilvear, 1997; Marcus, 2002; Fonstad and Marcus, 2005; Carbonneau *et al.*, 2006). In these cases where the stream is clear, the full bathymetry of the channel can be retrieved with photogrammetry either using a classic approach (Westaway *et al.*, 2003; Feurer *et al.*, 2008; Lane *et al.*, 2010), or an SfM approach (Woodget *et al.*, 2015; Dietrich, 2016). Finally, bathymetric LiDAR using a green laser has been in use for several years and is now available for deployment in rivers using manned airborne platforms (e.g. Kinzel *et al.*, 2007; Bailly *et al.*, 2010; Legleiter *et al.*, 2016). However, readers should note that all these methods suffer from the same limitation: water clarity. Radiometry and photogrammetry methods must have a clear view of the riverbed and are therefore limited to very low levels of turbidity and suspended sediment. Active methods based on LiDAR are somewhat more robust since a laser pulse is capable of penetrating turbid water, but in practice the increased signal noise caused by suspended particles means that the improvement is marginal. Ultimately, ground RS with intensive measurements from a boat is the only way to obtain accurate depth predictions for heavily turbid flows.

Characterization of fluvial corridor features: from reach to network and global scales

At the reach scale, river corridors can be seen as complex mosaics of distinct spatial units resulting from interactions between sediment, water, and vegetation. Fryirs and Brierley (2012) define these landforms as the 'building blocks' of the fluvial mosaic, but other terms have been proposed, such as geomorphic units, hydraulic units, physical habitats, meso-habitats and biotopes (Milan *et al.*, 2010; Wyrick *et al.*, 2014; Wheaton *et al.*, 2015; Belletti *et al.*, 2017). Some recent works combine multisource RS data from different sensors to better classify, characterize and model these building blocks (Bertoldi *et al.*, 2011; Legleiter, 2012; Williams *et al.*, 2014; Wyrick *et al.*, 2014; Demarchi *et al.*, 2016), as well as their physical properties, such as temperature (Wawrzyniack *et al.*, 2016).

Reach-scale features are traditionally mapped by means of expert-based approaches based on interpretation of available imagery, which may be used in complement with high-resolution topography (e.g. Dietrich, 2016). Topographic and morphometric signatures can be systematically extracted from high-resolution DEMs, allowing the prediction of fluvial landscape features such as channel heads (Clubb *et al.*, 2014), floodplains and terraces (e.g. Clubb *et al.*, 2017), morphological units (Cavalli *et al.*, 2008) or river reach features (Schmitt *et al.*, 2014). Automatic or semi-automatic algorithms to map river features started to emerge recently to improve the reproducibility of mapping products, and to reduce the time for mapping. Image classification is often a first step required to focus the application of algorithms to specific features in the image. To this day, a cost-effective method for classifying river features is still lacking and the first step of data processing is often one of the most laborious. Over the last decade, object-based image analysis (OBIA) has slowly developed as a step change allowing for enhanced image classification (Blaschke, 2010; Blaschke *et al.*, 2014). In contrast, the rapid developments in machine learning, deep learning and artificial intelligence are now beginning to cross over to the environmental sciences. Casado *et al.* (2015) demonstrated that a low-complexity, shallow, artificial neural network (i.e. a multilayer perceptron) was capable of identifying geomorphic features in a short river reach with an accuracy of 81%. Recently, Buscombe and Ritchie (2018) use a large dataset to demonstrate that a convolutional neural network (CNN) could be adapted to fluvial imagery in order to classify images and report mean F1 scores ranging from 88% to 98%. Carbonneau *et al.* (2019) developed a novel approach dubbed 'CNN-supervised classification', which uses a pre-trained CNN to replace the user input in traditional supervised classification. They report mean F1 scores ranging from 90% to 98%. The result of 90% reported in Carbonneau *et al.* (2019) is for rivers that were never seen by the classifier during the training phase. This suggests that deep learning could deliver a quasi-universal classifier capable of matching human performance when visually establishing the semantic classes of a river image.

In the case of vegetation and the riparian zone, recent years have seen significant gains in terms of resolution and detail (Bertoldi *et al.*, 2011; Dufour *et al.*, 2012, Kasprak *et al.*, 2012; Abalharth *et al.*, 2015; Atha and Dietrich, 2016). The ability to identify vegetation composition, including at the species scale, and to describe vegetation structure has greatly increased (Kaneko and Nohara, 2014; Riedler *et al.*, 2015; Husson *et al.*, 2016; Michez *et al.*, 2016; Bywater-Reyes *et al.*, 2017; Hortobágyi *et al.*, 2017; Loicq *et al.*, 2018). This is due to the integration of structural information provided notably by LiDAR data (Charlton *et al.*, 2003; Farid *et al.*, 2006; Antonarakis *et al.*, 2008; Geerling *et al.*, 2009; Johansen *et al.*, 2010; Michez *et al.*, 2017; Laslier *et al.*, 2019a). Indeed, LiDAR data can be used at the reach scale to assess vegetation roughness (Straatsma and Baptist, 2008), to monitor vegetation volume changes following a flood event at a very fine scale (Milan *et al.*, 2018), to identify tree genera at individual scale (Ba *et al.*, 2019), and many other attributes such as vegetation height, crown diameter canopy closure, vegetation density, age class or stream shading (Michez *et al.*, 2017; Laslier *et al.*, 2019a) (Figure 7). The ability to identify vegetation composition, including at species scale, has also greatly increased with the development of hyperspatial (Kaneko and Nohara, 2014; Husson *et al.*, 2016; Michez *et al.*, 2016; Bedell *et al.*, 2017; Laslier *et al.*, 2019b) and hyperspectral data (e.g. Peerbhay *et al.*, 2016; Rodríguez-González *et al.*, 2017). Mapping efforts from RS data also detect specific features such as instream wood distribution (Atha, 2014; Ulloa *et al.*, 2015), wood deposits (Marcus *et al.*, 2002, 2003) or instream wood characteristics and volumes in riverine environments (Boivin and Buffin-Bélanger, 2010; Tonon *et al.*, 2014).

In recent decades, important efforts have been made for network-scale mapping of fluvial environments (Alber and Piégay, 2011; Demarchi *et al.*, 2016) and riparian zones (Goetz, 2006; Johansen *et al.*, 2007; Clerici *et al.*, 2014;

Michez *et al.*, 2017). Notebaert and Piégay (2013) studied the present variability of floodplain width in the entire Rhône basin by combining digital terrain models, historical maps and other GIS layers (hydro-ecoregions, geological maps). They highlighted the contribution of inherited landscapes from tectonic processes and glaciations. Such approaches have also been used to map geomorphic units using aerial infrared orthophotos only (Bertrand *et al.*, 2013a) or combined with Li-DAR DEM (Demarchi *et al.*, 2017) (Figure 8). Another example is the method for regional scale automatic mapping of unvegetated patches in headwater catchments based on an object-based image analysis of infrared orthophotos and Landsat 7 ETM+ images developed by Bertrand *et al.* (2017). This has been successfully applied in the Southern French Alps to assess regional-scale sediment supply conditions in relation to debris-flow triggering, and more recently to link suspended load hysteresis patterns and sediment sources configuration in alpine catchments (Misset *et al.*, 2019). Concerning the riparian zone, the method can be used from large-scale delineation of buffers to the description of the zone characteristics at watershed to continental scales (Johansen *et al.*, 2010; Clerici *et al.*, 2014; Cunningham *et al.*, 2018). Fine-scale approaches now extend to the network scale. Michez *et al.* (2017) compared rivers of different regions in Belgium based on the ratios of channel width and depth to the basin area.

Comprehensive, systematic analyses of the different predictors of fluvial patterns, as well as predictions of future channel evolution (if any of these predictors are altered), may now be achieved at a global level, at least for medium-size rivers, using existing pre-processed, remotely sensed archives and platforms. For instance, the Global Width Database for Large Rivers (GWD-LR) contains channel widths between 60° S and 60° N extracted using the SRTM Water Body Database (Yamazaki *et al.*, 2014). Considerable advances may be achieved by using global archives to interrogate or predict
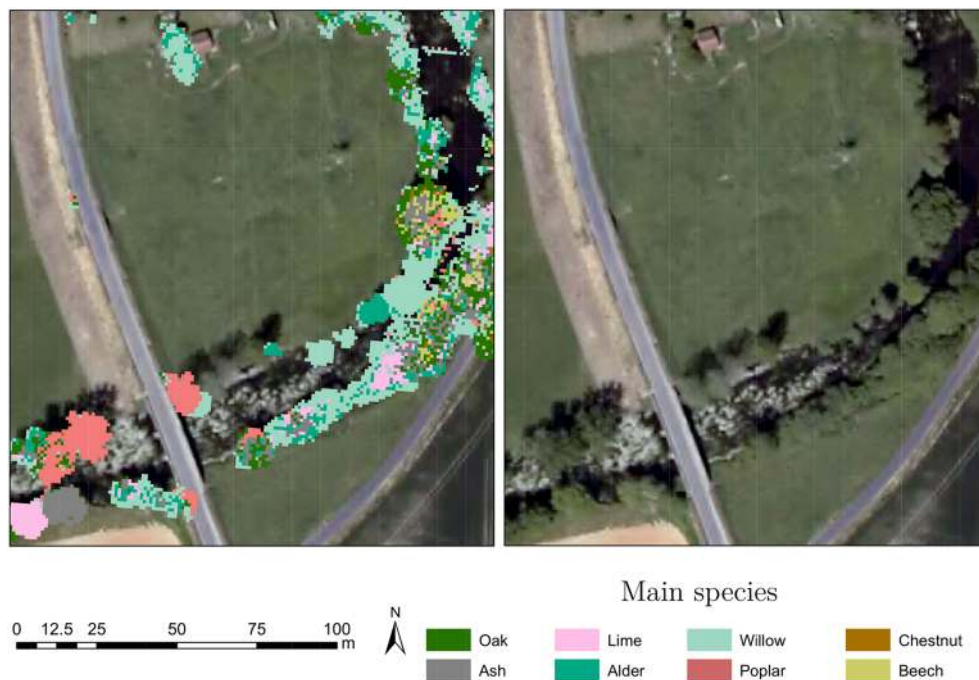

Main species

Oak | Lime | Willow | Chestnut
Ash | Alder | Poplar | Beech

0 12.5 25 50 75 100 m

Figure 7. Riparian genera map obtained from LiDAR data and tree morphological patterns (Séffune River, western France). Tree crown morphology and internal structure indicators were computed from the 3D point clouds of two surveys (summer and winter; *n* = 144 indicators) and the most discriminant indicators were selected using a stepwise quadratic discriminant analysis allowing the number of indicators to be reduced to less than 10 relevant indicators. The selected indicators were used as variables for classification using support vector machine. Overall accuracy ranges from 80% for three genera to 50% for eight genera. With eight genera, the identification remains a challenge, as for one tree crown predicted pixels can be mixed. (From Laslier *et al.*, 2019a.) [Colour figure can be viewed at wileyonlinelibrary.com]
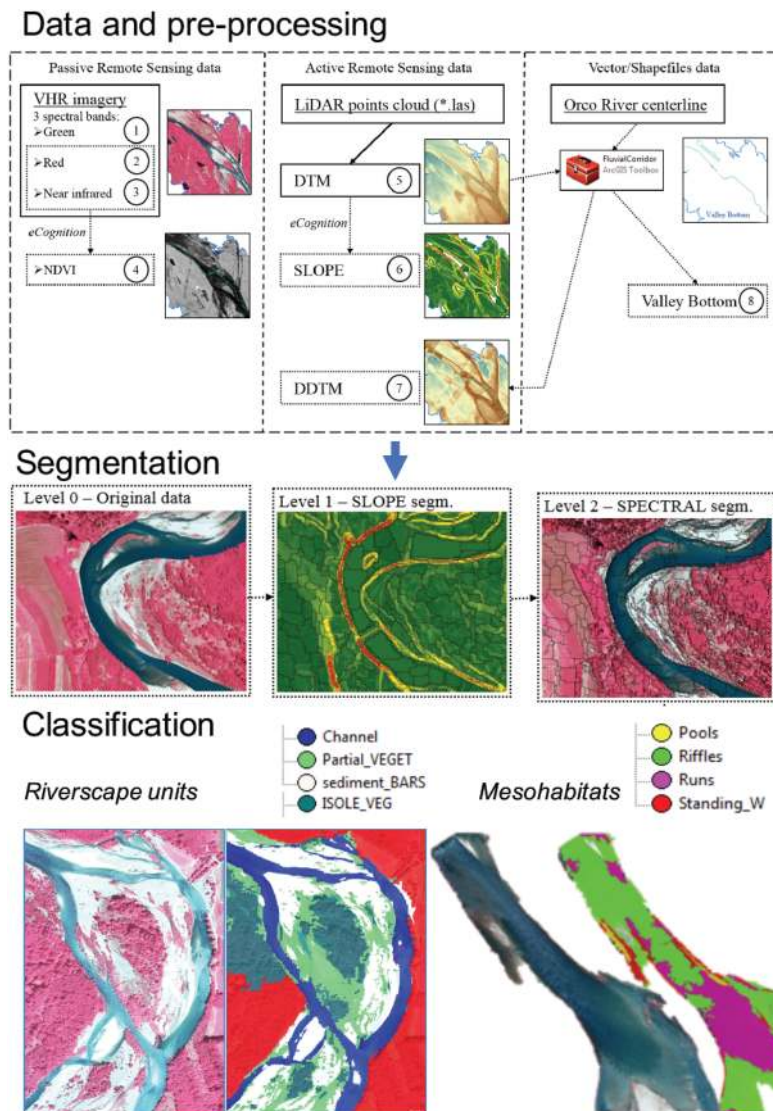
Figure 8. Workflow of the multilevel, object-based methodology developed for the classification of riverscape units and in-stream mesohabitats. Top row shows data type used (multispectral and LiDAR-derived DTM); central row describes the OBIA steps to derive topographically and spectrally homogenous units; the bottom row displays classification results for riverscape units (on the left) and mesohabitats (on the right). (From Demarchi *et al.*, 2016) [Colour figure can be viewed at wileyonlinelibrary.com]

channel form, e.g. using remotely sensed measurements of global surface water (Pekel *et al.*, 2016), global river widths extracted from gauging stations worldwide (Allen and Pavelsky, 2018) or a global geospatial river reach hydrographic information database (including river networks, watershed boundaries, drainage directions and flow accumulations) derived from SRTM high-resolution elevation data (HydroSHEDS; Lehner *et al.*, 2008). Recently, a Global River Classification (GloRiC) database has been built on such global archives (Ouellet Dallaire *et al.*, 2019). The Global River Classification (GloRiC) database provides 127 river reach types for all rivers globally, based on variables such as hydrology, physiography and climate, fluvial geomorphology, water chemistry and aquatic biology (Ouellet Dallaire *et al.*, 2019). Pan-European riparian corridors have also been generated (Weissteiner *et al.*, 2016).

Fluvial processes: from decadal landform changes to real time observations

The notable advances in fluvial RS during the last two decades have been particularly helpful for the investigation of channel responses to environmental driving forces in a very large variety of physical settings, and for the assessment of fluvial processes.

Riverscape changes
Landform changes (sediment erosion, deposition, channel shifting) investigated at decadal scales are now approached at inter-annual or even event-based scales. Until the mid-1990s, when the first high-resolution DEMs of river channels were reported (Lane *et al.*, 1994, 1995), it was only possible to constrain erosion and deposition processes acting in river channels by using time-consuming repeated terrestrial topographic surveys, generally along predefined monumented cross-sections positioned at regularly spaced intervals along river reaches. With the advent of modern topographic surveying solutions, it is possible to rapidly cover several kilometres of river reaches with dense 3D point clouds of high accuracy and precision. LiDAR surveys (ground-based or airborne) and SfM photogrammetry are the two technological solutions available for a rapid and continuous topographic survey of river channels. Both solutions offer comparable precision, accuracy and density of information for unvegetated and exposed terrains (a compilation of precision and accuracy values for

airborne LiDAR datasets in gravel-bed rivers is available in Lallias-Tacon *et al.*, 2014), but with LiDAR it is possible to capture the topography of vegetated surfaces, provided that the density of the vegetation cover is not too high (e.g. Charlton *et al.*, 2003). The most recent advances in LiDAR technology also offer the possibility to combine different LiDAR wavelengths to capture during the same flight the topography of exposed and submerged surfaces of river channels (Mandlburger *et al.*, 2015), which can be a decisive advantage for large river channels. Case studies making use of sequential and distributed high-resolution RS data to reconstruct short-term channel changes are now common in the literature (see recent review from Vericat *et al.*, 2017). Differential topography based on sequential LiDAR or SfM datasets is used to produce distributed maps of erosion and deposition of channel reaches, to use this information to reconstruct sediment budgets, and also to back-calculate bedload transport using the morphological approach (Passalacqua *et al.*, 2015; Vericat *et al.*, 2017; Antoniazza *et al.*, 2019). The order of magnitude of detectable elevation changes with those data is generally around 10–20 cm, but this depends on the sensor accuracy or flight height as well as the properties of the investigated surfaces. Several studies document the negative effect of vegetation, local slope and surface roughness on the level of detection of topographic change in river channels (e.g. Wheaton *et al.*, 2010; Milan *et al.*, 2011; Lallias-Tacon *et al.*, 2014). It is also recognized that these data need a careful inspection and correction of systematic errors in spatial positioning or elevation before computing a sediment budget, as this error may have a strong impact on the integrated volumes of sediment erosion and deposition (Anderson, 2019). Stable areas may be used to evaluate the systematic error, and to coregister the sequential datasets before computing the sediment budget (e.g. Lallias-Tacon *et al.*, 2014; Passalacqua *et al.*, 2015; Anderson, 2019). Topographic differencing using high-resolution datasets have been successfully used to investigate a large range of fluvial processes, such as bank erosion (Thoma *et al.*, 2005; Jugie *et al.*, 2018), braided channel responses to flow events (Lane *et al.*, 2003; Milan *et al.*, 2007; Hicks *et al.*, 2009; Lallias-Tacon *et al.*, 2014) and channel response to restoration projects (Campana *et al.*, 2014; Heckmann *et al.*, 2017) (Figure 9).

Classically, vegetation dynamics have been analysed using temporal series of remotely sensed images (satellites, aerial, UAV, terrestrial, etc.) to monitor management actions such as ecological restoration (Norman *et al.*, 2014; Nunes *et al.*, 2015; Martínez-Fernández *et al.*, 2017; Bauer *et al.*, 2018; Martinez *et al.*, 2018). In many cases, the monitored processes impose a given temporal resolution and thus a given sensor/vector couple. For example, single events and intra-annual processes can be monitored using close-range terrestrial photography (Bonin *et al.*, 2014; Džubáková *et al.*, 2015) or UAV (Laslier *et al.*, 2019b), and inter-annual succession processes using UAV (Hervouet *et al.*, 2011; Räpple *et al.*, 2017) or airborne orthophotos (e.g. Michez *et al.*, 2017).

Real-time monitoring of fluvial processes

Fluvial processes can now be monitored in real time using ground-based imagery with high temporal or spatial resolution. Tauro *et al.* (2018) review the most commonly used and new techniques to measure and observe different hydrological variables, and notably the latest optical flow tracking techniques to estimate flow velocity and discharge, including large-scale particle image velocimetry (LSPIV; Le Coz *et al.*, 2010), particle tracking velocimetry (PTV; Tauro *et al.*, 2019), and Kanade–Lucas–Tomasi (KLT) flow tracking (Perks *et al.*, 2016). These techniques allow the computation of flow surface velocities using images of the river surface sampled with UAV
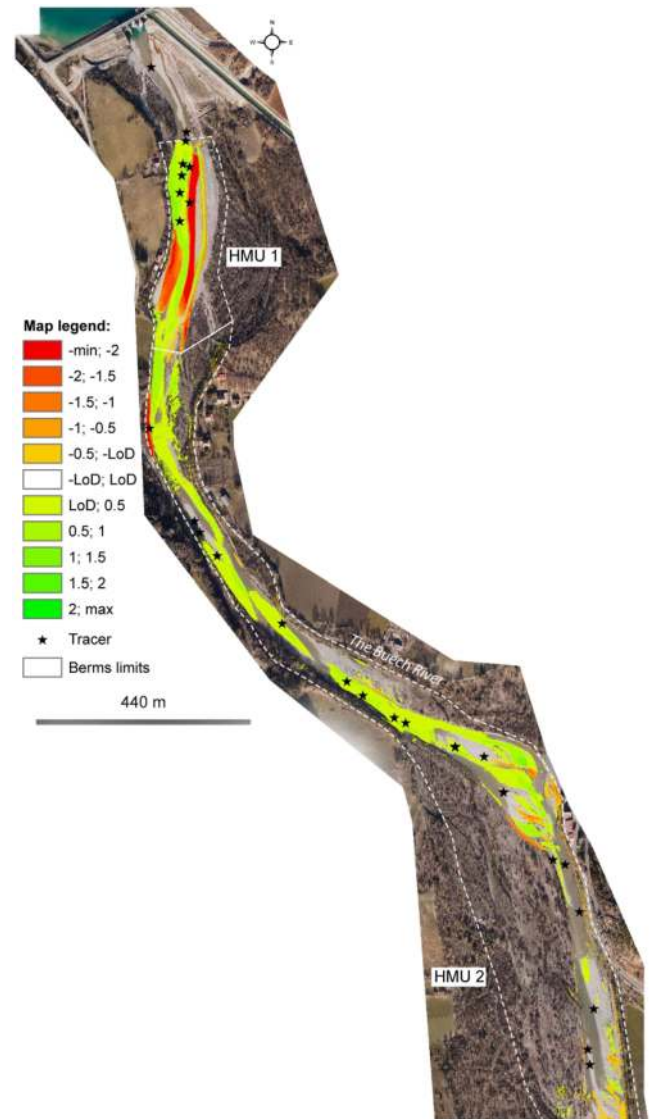

Figure 9. Monitoring of sediment wave propagation following a gravel replenishment operation downstream of a dam in the Buëch River (Southern French Prealps), using repetitive airborne LiDAR surveys and UHF active RFID tags (from Brousse *et al.*, 2019); the combination of HR topographic differencing before and after a 5-year flood and bedload tracing successfully allow us to detect the propagation of the artificially induced sediment wave, with a front located at 2.5 km from the dam. [Colour figure can be viewed at wileyonlinelibrary.com]

(Perks *et al.*, 2016), ground-based cameras or screenshots extracted from film (Le Boursicaud *et al.*, 2016). Natural tracers present at the flow surface are tracked, such as boils, surface ripples and driftwood, or artificial tracers such as cornstarch chips (Le Coz *et al.*, 2010). They have been increasingly used to measure and estimate surface flow velocity and discharge during floods (Muste *et al.*, 2011; Tauro *et al.*, 2016) in both gauged and ungauged basins, and proved to be a powerful approach when standard techniques fail or are difficult to deploy (Le Coz *et al.*, 2010).

Manual and automatic procedures have also been developed to monitor instream wood fluxes using ground cameras (MacVicar *et al.*, 2009). Kramer and Wohl (2014) used a time-lapse camera to observe and quantify wood fluxes in the subarctic Slave River, and stressed that an appropriate and site-specific sampling interval is key to achieve unbiased estimates. MacVicar and Piégay (2012) pioneered installing a video camera on the Ain River in France to describe the relation between wood transport and water discharge, and to construct and
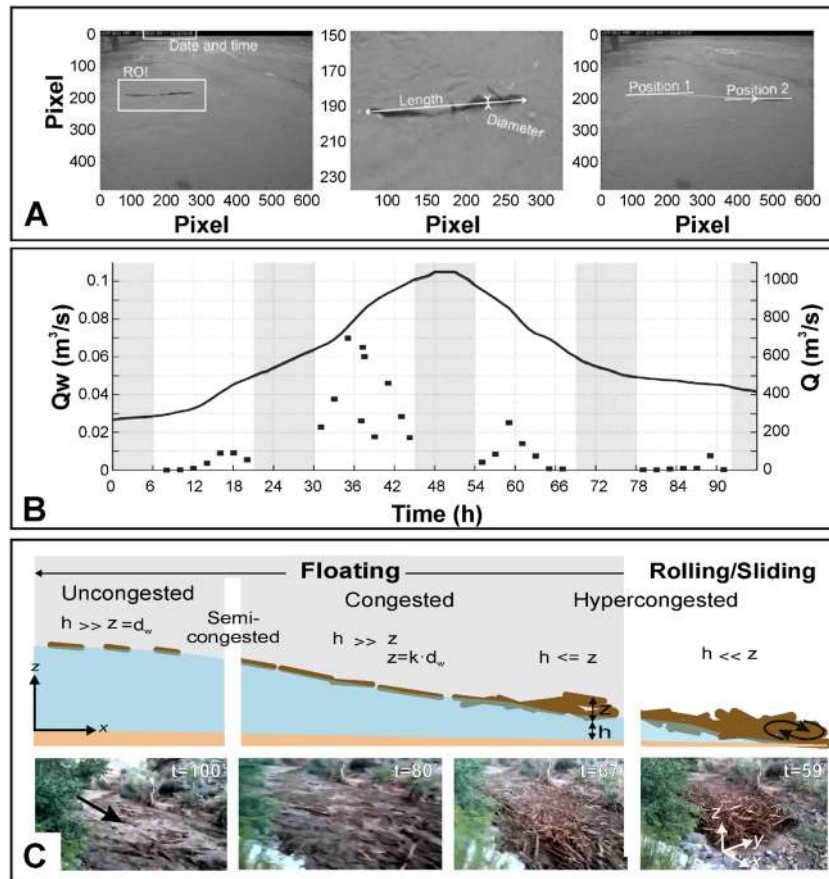
Figure 10. (A) Wood detection procedure using a video camera in the Ain River, France. Images show the region of interest (ROI) based on a visual detection of wood including measurement of date and time from time stamp, the precise location of end and side points to define the piece length, diameter and first position, and the definition of second position after advancing a user-determined number of frames to allow calculation of velocity and angular velocity. (B) Flood hydrograph and wood flux estimated based on video records during the event on 10–13 April 2008 (modified from MacVicar and Piégay, 2012). (C) Wood transport regimes characterized using home movies; the small images show the same river section (North Creek, USA) at different times (t), water depth (h) and wood flow depth (z); d_w, wood piece diameter; k, coefficient > 1 (modified from Ruiz-Villanueva et al., 2019). [Colour figure can be viewed at wileyonlinelibrary.com]

validate a wood budget for the reach upstream of the camera (Figures 10A and 10B). Boivin et al. (2017) used two video cameras to monitor the passage of wood during floods and ice-breakup events in the Saint-Jean River in Canada. As for flood discharge data (Le Coz et al., 2016), web-crowdsourced home movies have been recently used to define and characterize wood-laden flows (Ravazzolo et al., 2017; Ruiz-Villanueva et al., 2019) (Figure 10C). Automatic and semi-automatic wood detection procedures have been developed to track and quantify the wood discharge in the images (Benacchio et al., 2017), but the systematic application still requires further research (Piégay et al., 2019). Despite the limitations, monitored sites with cameras have significantly increased in recent years and will continue in the future.

Ground-based RS techniques for the indirect monitoring of bedload transport are also in an active phase of development. Seismic sensors such as impact sensors, geophones and seismometers are increasingly used as non-intrusive devices to detect and characterize bedload transport from ground vibrations generated by grain impacts (Burtin et al., 2011. 2016; Downs et al., 2016; Roth et al., 2016). Their deployment in near proximity to river channels, in relatively safe positions, is a great advantage compared to traditional seismic methods based on the deployment of plates or pipes in the active zone of bedload transport (e.g. Mizuyama et al., 2010; Rickenmann et al., 2012). The monitoring of bedload in large rivers with high water depths is also now possible with the use of acoustic sensors such as hydrophones (Belleudy et al., 2010; Geay et al., 2017). Although reliable

estimates of bedload flux with seismic and acoustic sensors still imply time-consuming field efforts for calibration with physical bedload samples, these RS solutions offer valuable continuous proxy records of sediment transport. These records have been successfully used to inform incipient motion and hysteresis in bedload rating curves, or to detect the passage of sediment pulses at river cross-sections (Belleudy et al., 2010; Geay et al., 2017; Burtin et al., 2016).

Developing Predictive Models using RS Information

RS technologies open new opportunities to assess future changes and potential physical or ecological responses. The technologies can be used to develop scenarios of change (Baker et al., 2004), pressure-impact models (Tormos et al., 2012), risk assessment (Bertrand et al., 2013a, 2013b) and, increasingly, process-based models. RS technology is moving towards the possibility of mapping entire river networks consistently, extensively (from geomorphic features and processes to acting pressures) and over time (Carbonneau et al., 2012).

Biogeomorphic models

Abiotic and biotic interactions have long been an important part of fluvial geomorphology, given the role of riparian vegetation (Corenblit et al., 2007, 2009; Gurnell et al., 2012) and
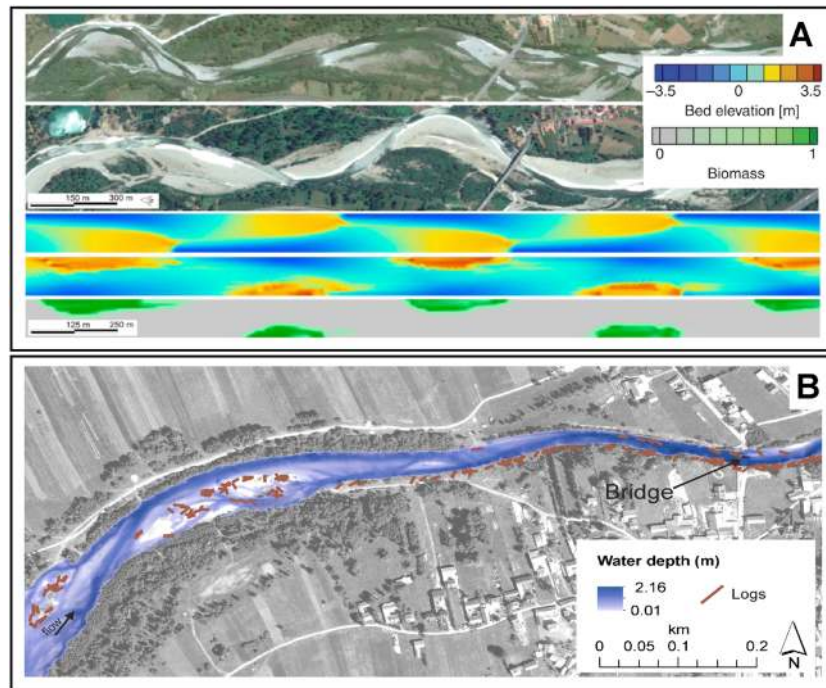
Figure 11. (A) Aerial images of the Magra River near Aulla (Italy) in 2007 (up) and in 2011 (down) and bed topography before a simulated flood sequence, after four floods and simulated biomass distribution (from Bertoldi *et al.*, 2014). (B) Simulated water depth and logs deposited along the Czarny Dunajec River reach at a discharge of 28 m^3 s^{-1} (from Ruiz-Villanueva *et al.*, 2017). [Colour figure can be viewed at wileyonlinelibrary.com]

large wood (Ruiz-Villanueva *et al.*, 2016), but also aquatic macrophytes/biofilm (which can be a constraint to extract water depth or grain size from RS data) and the other biotic components.

There is scope to increase the linkage between disciplines by incorporating remotely sensed information (such as land cover change or normalized difference vegetation index) within future predictive models of river changes. Models are able to simulate complex fluvial processes including water–sediment–vegetation–wood feedbacks. First attempts have been made to model the effect of flow and climate change on vegetation dynamics (Hammersmark *et al.*, 2010), the succession of riparian vegetation as a function of scour disturbance, shear stress and flood duration using the CASiMiR vegetation model (Benjankar *et al.*, 2014) or the effects of vegetation growth on meander bank stability (Perucca *et al.*, 2007). Recent developments have enhanced computational fluid dynamic models by including vegetation and wood dynamics (Bertoldi *et al.*, 2014; Ruiz-Villanueva *et al.*, 2014b; Figure 11). These advanced models open the door for investigations of how changes in the water, sediment or wood regime may affect the fluvial response, which is fundamental for river management. Still the full coupling of hydro-, morpho- and vegetation dynamics remains challenging. One key constraint is to gather the required high-resolution input and validation data.

Catchment-scale models

Until a few years ago, catchment-scale models were limited by the lack of suitable datasets, but they are now a flourishing research area that is providing valuable evidence to support the management and planning of river systems. Catchment-scale models have become feasible owing to the availability of DEMs with a high enough resolution to represent river features (e.g. Passalacqua *et al.*, 2015). The coupling of DEMs with large-scale distributed hydrological models (Van Der Knijff *et al.*, 2010) can now be used to characterize sediment and nutrient

transport across entire networks (Jain *et al.*, 2006; Barker *et al.*, 2009; Bizzi and Lerner, 2015). This context has fostered the development of sediment models to assess how sediment is routed through a network and how the various sediment sources within the basin generate different sediment connectivity patterns (Cavalli *et al.*, 2013; Heckmann and Schwanghart, 2013; Czuba and Foufoula-Georgiou, 2014; Heckmann *et al.*, 2015, 2018; Parker *et al.*, 2015; Czuba, 2018). For instance, the CAtchment Sediment Connectivity And DElivery (CASCADE) modelling framework enables a quantitative, spatially explicit analysis of network sediment connectivity with potential applications in both river science and management (Schmitt *et al.*, 2016; Figure 12). In the Mekong delta, understanding the cumulative effects of constructed and planned dams helps identify new solutions addressing both economic and environmental objectives (Schmitt *et al.*, 2018a, 2018b, 2019).

Similarly, in the case of instream large wood (i.e. fallen trees, trunks, rootwads and branches), models have been developed to assess wood supply and transfer through catchments using novel datasets (Ruiz-Villanueva *et al.*, 2016). Wood is supplied to rivers by complex recruitment processes (e.g. landslides, bank erosion) with large spatial and temporal variability, which makes predictions challenging. Models fed with remotely sensed data, such as aerial imagery and forest cover information, enable the simulation and identification of recruitment processes and sources and the estimation of wood supplied volumes (Gregory and Meleason, 2003; Mazzorana *et al.*, 2009; Ruiz-Villanueva *et al.*, 2014a; Cislaghi *et al.*, 2018). High-resolution canopy models obtained from LiDAR or photogrammetry may provide more accurate estimation of wood volumes (Steeb *et al.*, 2017; Gasser *et al.*, 2019). Scenarios based on forecasted climate change alterations of vegetation cover, flow regimes and human activities can be also designed to explore and quantify the range of variability of instream wood supply, and to make predictions about how differences in river and forest management may alter instream wood supply (e.g. Cislaghi *et al.*, 2018).
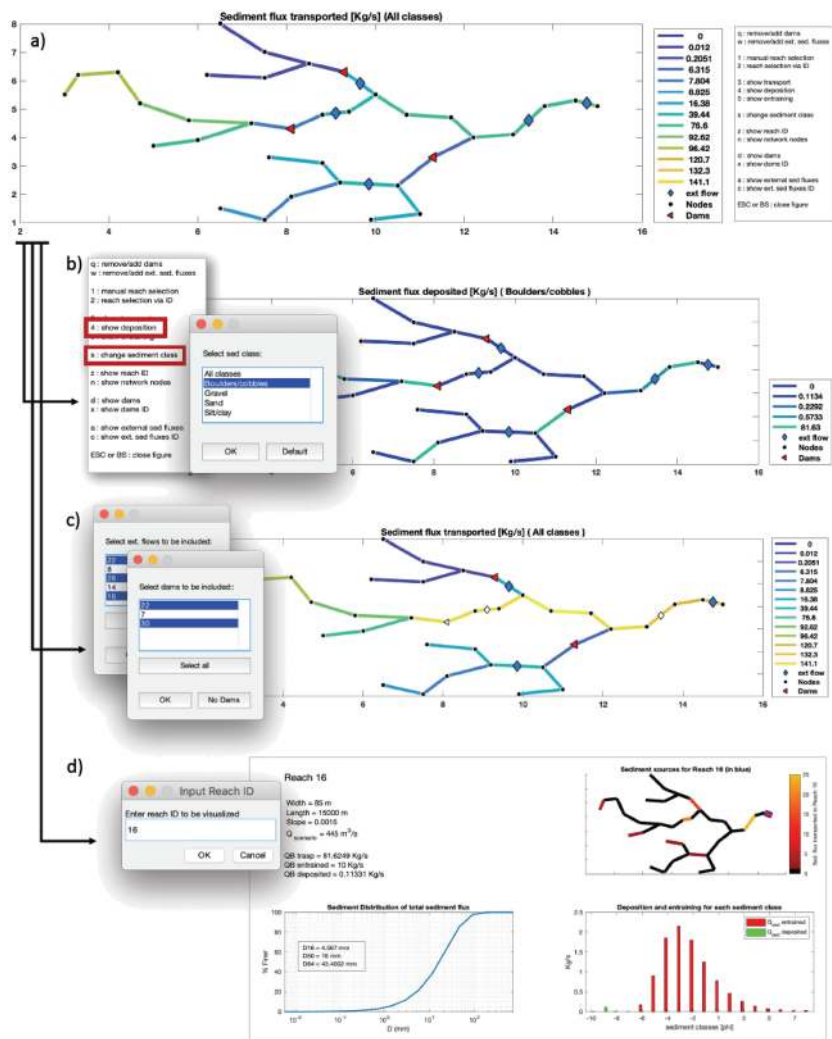
Figure 12. Examples of plots obtained from CASCADE toolbox (from Tangi *et al.*, 2019). The tool allows analysis of various properties of sediment connectivity in an interactive manner. (a) Total sediment transported (kg s^{-1}) in the network. (b) Patterns of deposition for a single sediment class out of the 18 considered in the model (in this case boulders/cobbles). (c) Changes in total sediment transport caused by the removal of one dam and two external sediment flows. (d) Analysis of grain size distribution, sediment sources and deposition and entrainment in a specific reach. Each step can be interactively controlled by the user using a graphical interface. [Colour figure can be viewed at wileyonlinelibrary.com]

Understanding future changes consistently at the network scale to inform river management requires an integrated approach, combining local field data with current large data archives and computational tools, and drawing upon a range of disciplines such as hydrology, climatology or ecology. Hydrology can help us understand patterns in remotely sensed rivers by better incorporating information on flow non-stationarity, catchment characteristics, large-scale river flow archives and hydrologic modelling. Integrating geomorphological analyses with climatology is increasingly important for understanding how climate change and large-scale climate variability may alter sediment dynamics, vegetation patterns, streamflow and, ultimately, channel adjustment (Darby *et al.*, 2013; Slater *et al.*, 2019a).

Forthcoming Resources

Emerging data, tools and geospatial analyses are generating cost-effective and promising opportunities to inform river management worldwide. This section provides an overview of datasets, tools and web resources available to assess river status and changes.

New acquisition opportunities

One of the principal technological challenges in RS is to increase the scale and spatial coverage at which it is possible to obtain a continuous and high-resolution reconstruction of the Earth's surface. This in turn allows an increase in the number of forms and processes that can be identified using a variety of spatial and spectral information. However, the cost of RS technology generally increases rapidly with increasing resolution, along with associated costs in terms of data handling and processing and the technical skills required to analyse the products of new aforementioned sensors. Despite the growing availability of low-cost airborne solutions such as UAV, the challenge of surveying entire rivers at sub-decimetric resolutions remains considerable.

In recent years, the growing popularity of the consumer drone market has meant that models equipped with moderate-quality imaging sensors are now available at less than 2500 euros (in 2019). The drive to produce imagery and video footage for mass consumption has benefited scientists who require images with relatively low distortion and a good dynamic range. Furthermore, ease of operation for the mass consumer market means that these low-cost airborne platforms are capable of automated flight, have single-phase, non-
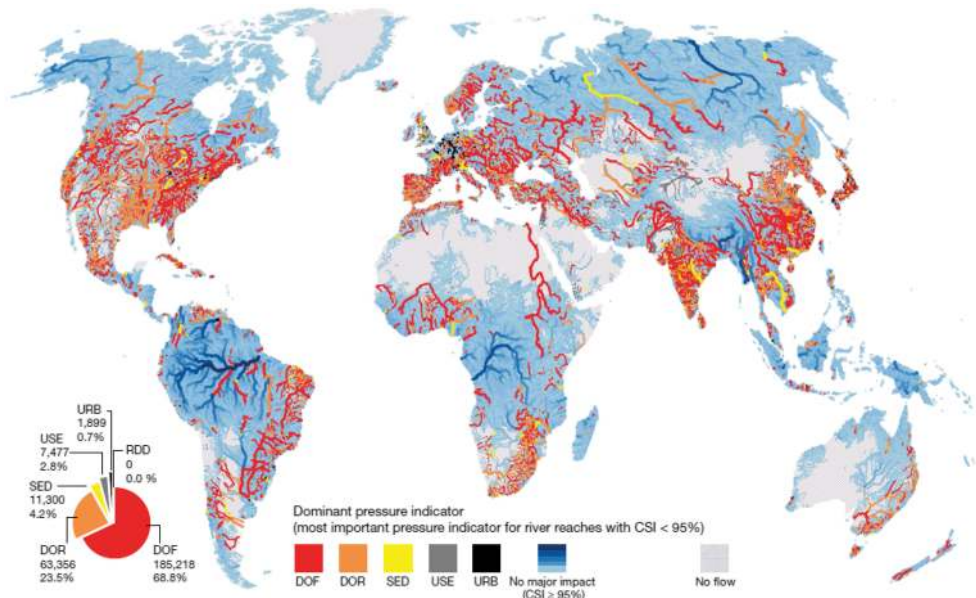
Figure 13. Dominant pressure indicator for global river reaches below a given connectivity status index (CSI) threshold (95%). Pressure indicators include the DOF (degree of fragmentation), DOR (degree of regulation), SED (sediment trapping), USE (consumptive water use) and URB (urban areas). Inset shows the number and proportion of river reaches per dominant pressure indicator at the global scale. (From Grill *et al.*, 2019) [Colour figure can be viewed at wileyonlinelibrary.com]

corrected GPS systems and, increasingly, active collision avoidance systems. Expanding the area of operations for drone surveys remains at the research frontier. There are two important issues to confront. First, the current regulatory trend in most nations is to limit drone operations to the line of sight of the pilot. This obviously constrains the range of operations to a radius of a few hundred metres per flight. In practice, this means that a well-trained team of operators can currently survey 3–5 km of river corridor per day, depending on the relocation conditions and the amount of ancillary data required, such as surveyed ground control. Second, this use of ground control, long held as an absolute requirement, is currently being challenged (e.g. Carbonneau and Dietrich, 2017; James *et al.*, 2017).

If we look towards the near future, the resolution of Earth observation data from satellites is such that soon it should provide more information to characterize large to mid-sized river features and changes almost continuously in space and time. Mini-satellites provide almost daily images globally at 3–5 m resolution in the RGB and near-infrared bands (see https://www.planet.com/), and the SWOT satellite will soon observe major lakes, rivers and wetlands with unprecedented resolution. In the next few years, two major programs will supply more frequent images with better quality: Landsat 9, which will be launched in 2020; and Pleiades Neo, which will be composed of four satellites that will revisit the same scene twice daily, producing panchromatic images at 30 cm resolution – a higher spatial resolution than for airborne campaigns done by many national institutions since 1940s.

The increasing global data availability

High-resolution topographic and observed hydrological data have only been available for a few years at the global scale and are providing new ways to characterize river characteristics and trajectories. A better understanding of how fluvial systems vary globally will require close integration of geomorphic datasets with a range of hydrologic, climatic, topographic and biological data archives. Hydrologic data have become available for many countries via the Global Runoff Data Centre

(GRDC) and the World Meteorological Organization's Hydrological Observing System (WHOS). Crochemore *et al.* (2019) provide an analysis of the quality of 21 586 river flow time series from 13 openly accessible hydrological archives. Recent global datasets such as the Global Streamflow Indices and Metadata Archive (Do *et al.*, 2018) have used these archives to compute global river catchment attributes. Global discharge reanalysis data from 1979 to near real time has also recently become available through the Copernicus Climate Data Store (CEMS GloFAS, 2019). DEM-derived topographic signatures (e.g. Amatulli *et al.*, 2018) may also be used to provide a more systematic assessment of the spatial distribution of different river types, with the advent of high-resolution DEMs such as MERIT (Yamazaki *et al.*, 2017) or the 90 m resolution TanDEM-X (Archer *et al.*, 2018). A systematic understanding of channel signatures will also require the integration of these topographic signatures with large-scale climatic and anthropogenic data, e.g. by using global high-resolution reanalysis products such as ERA5 from Copernicus ECMWF (Hersbach *et al.*, 2018), information on global reservoirs and dams (Lehner *et al.*, 2011; Grill *et al.*, 2019; Figure 13) or suspended sediment data (e.g. the Land2Sea database; Peucker-Ehrenbrink, 2009).

Emerging geoprocessing tools

Data are increasingly available from a number of freely and openly accessible repositories. However, to realize the full potential of big data, rapid access and efficient processing capabilities are required (Giuliani *et al.*, 2017). With the development of new data and sensors we must also develop our collective ability to manage and analyse these data. The increasing development of 3D information provided by photogrammetry and LiDAR or infra-annual time series of VHR images, for instance, potentially opens many scientific and applied issues related to the interpretation and understanding of riverscape functioning, but also raises the question of the chain of actors involved in data acquisition, processing and utilization.
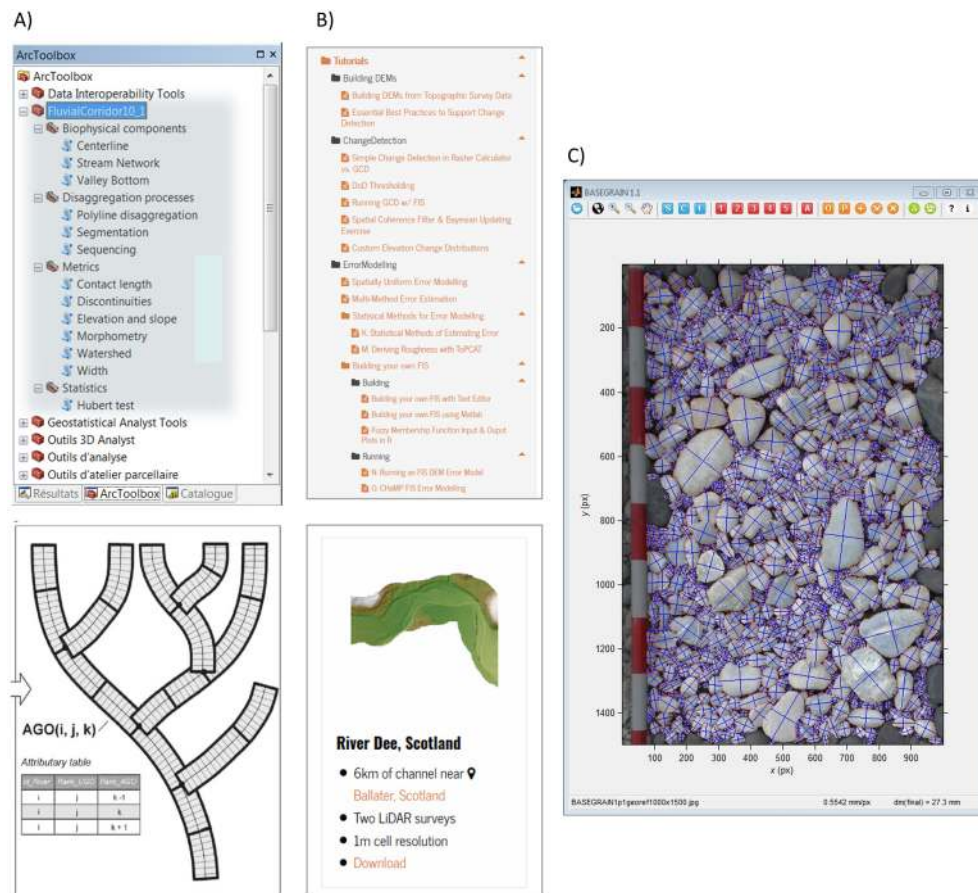
Figure 14. Example of tools/interfaces available online to measure characteristics of fluvial corridors. (A) The Fluvial Corridor Toolbox (FCT) within the ArcGIS Arc Toolbox (modified from Roux et al., 2015) and view of generic spatial units for characterizing aggregated geographical objects at the network scale (https://github.com/EVS-GIS/Fluvial-Corridor-Toolbox-ArcGIS). (B) Website views (tutorial and dataset example) of Geomorphic Change Detection software (http://gcd.riverscapes.xyz/) (Wheaton et al., 2010). (C) Example of image output showing grain detection using BaseGrain software (https://www.ethz.ch/content/specialinterest/baug/laboratory-vaw/basement/en/download/tools/basegrain.html) (modified from Detert and Weitbrecht, 2012.) [Colour figure can be viewed at wileyonlinelibrary.com]

Deriving insights on fluvial characteristics from very large datasets requires computational tools and automation. There has been a rise in computational hydrology, ecology and geomorphology over the last decade thanks to the uptake of open-source programming languages such as R and Python. For example, hydrologists have developed many packages supporting the entire hydrological 'workflow', including meteorological and hydrological data retrieval via application programming interfaces; data extraction at catchment scales from global gridded data; many different catchment hydrological models; and packages specifically designed for statistical analyses and data visualization (Slater et al., 2019b). Many hydrological and ecological packages already exist for automated satellite image processing, handling and manipulation of RS data, correcting and rescaling satellite imagery, or for analysing remotely sensed vegetation data. For R users, the CRAN task views provide lists of packages for different areas of research, many of which are relevant for fluvial geomorphology, including areas such as time series analysis, reproducible research, machine learning and spatial data analysis (https://cran.r-project.org/web/views/). Supervised classification is on the verge of undergoing a fundamental change whereby general pre-trained deep learning models are used to obviate the labour-intensive phase of manual image labelling for land-cover classification. Most notably, the machine learning algorithms used by Carbonneau et al. (2019) are fully in the open-source realm. It would therefore seem likely that artificial intelligence approaches are set to overtake, or perhaps absorb, existing approaches of 'object-based image analysis'.

Computational fluvial geomorphologists are also increasingly using and developing toolboxes to understand and quantify river landscape change (Figure 14; for a recent review see Fryirs et al., 2019). For instance, the open-source LSDTopoTools software is used for topographic analysis, channel network extraction, chi analysis, calculation of erosion rates, hilltop flow routing and relief metrics, and/or topographic extraction of floodplains and terraces (Mudd et al., 2018). The RiVMAP MATLAB toolbox or the cmgo R package can be used to measure channel widths, the locations and rates of migration, accretion and erosion, and the space–time characteristics of cutoff dynamics (Golly and Turowski, 2017; Schwenk et al., 2017). The CASCADE toolbox (Tangi et al., 2019) provides assessment of sediment connectivity at the network scale and enables screening impacts of many infrastructure portfolios. Other toolboxes include the Fluvial Corridor Toolbox (https://github.com/EVS-GIS/Fluvial-Corridor-Toolbox-ArcGIS; Roux et al., 2015), the NCED Stream Restoration Toolbox (Lauer, 2006), the River Bathymetry Toolkit (McKean et al., 2009) and the RVR Meander toolbox (Abad and García, 2006) to measure channel features and processes (e.g. migration rates). The River Analysis and Mapping engine (RivaMap) has been developed to facilitate the computation of large-scale hydrography datasets (i.e. extracting the river centreline and width) from Landsat data in a short time period (Isikdogan et al., 2017). The Valley Bottom Extraction Tool (V-BET; Gilbert et al., 2016) and the Valley Bottom Confinement Tool (VBCT; O'Brien et al., 2019), used across networks, allow the categorization of channel confinement categories and degrees. The

shape/morphology of different channel units (i.e. concave, convex and planar surfaces) can be mapped along reaches using the Geomorphic Unit Tool (GUT) (Wheaton *et al.*, 2015; Kramer *et al.*, 2017) as well as the Geomorphic Change Detection (GCD) software for sediment budgeting Wheaton *et al.*, 2010; see www.riverscapes.xyz). Digital grain sizing algorithms developed by Buscombe (2013) (pyDGS: http://digitalgrainsize.org/) and Detert and Weitbrecht (2012; Basegrain: https://basement.ethz.ch/download/tools/basegrain.html) are also available online as well as an algorithm for calculating roundness index (Cassel *et al.*, 2018) (https://github.com/EVS-GIS/2D-Roundness-Toolbox). Most of these datasets and toolboxes are free to use, globally applicable and represent a valuable resource for researchers and managers worldwide.

Online platforms and repositories

Sharing data and knowledge is an indispensable component of stakeholder-integrated problem solving (Lehmann *et al.*, 2017; Dick *et al.*, 2018). The wide range of automatic feature extraction toolboxes listed above indicates that mapping/detecting geomorphic features is possible. However, collective organization and repository tools are needed. One example is the international long-term ecological research (ILTER) network, which gathers more than 600 sites worldwide in a broad variety of terrestrial, freshwater and marine environments (Haase *et al.*, 2016; Dick *et al.*, 2018). Networking is based on the DEIMS-SDR data system (Dynamic Ecological Information Management System – Site and Dataset Registry: https://data.lter-europe.net/deims/), which includes a repository of remotely sensed data. Similarly, a spatial data infrastructure (SDI) has been developed within the Human–Environment Observatories network, which brings together 13 French and international observatories, including river observatories (Chenorkian, 2012). Web GIS, metadata and other visualization tools developed in this SDI are available for scientists and stakeholders. Additionally, the Data Center of the San Francisco Estuary Institute provides a broad range of tools and web services to upload, access and visualize remotely sensed datasets and other GIS layers to support and inform natural resource management in the area (Grosso and Azimi-Gaylon, 2018; https://www.sfei.org/sfeidata.htm). In the Earth surface sciences, the Community Surface Dynamics Modeling System (CSDMS) maintains a code and metadata repository for numerical models and scientific software tools (https://csdms.colorado.edu). In hydrology, Lehman *et al.* (2014) reviewed innovative global observation solutions that provide a suite of hydrological standard specifications to the BRIdging Services Information and Data for Europe (BRISEIDE) project to visualize, manage and process geospatial resources useful for hydrological model development. Google Earth and NASA WorldWind also offer capabilities to visualize spatiotemporal data. An example is the Global Dam Watch initiative (http://globaldamwatch.org/), which aims to maintain the world's most comprehensive and freely available global dam data, including a repository for the GlObal georeferenced Database of Dams (GOOD[2]) obtained from Google Earth satellite imagery, and an open list of existing dam data available at regional and global scales.

Prospects for the Remote Sensing of Anthropocene Rivers

RS has become a key tool to characterize past, current and future fluvial corridor conditions, and provides information almost as important as field information. In recent decades, fluvial RS has mainly been used in the sciences, but now these techniques are increasingly used by consultants too. Many river management consultancies utilize drones, equipped with different sensors, as well as SfM techniques or classical images in monitoring studies. Ground cameras are also widely employed to study processes in action. RS has become one of the most common tools in the geomorphologist's toolkit, and one might almost say the 'field tradition' is in the past! What, therefore, are the future research prospects for RS? Some research objectives are likely to be rapidly attained whereas others are still inaccessible. Ten future avenues for RS of Anthropocene rivers are:

1 *Exploring existing data more deeply,* such as national (maps and aerial photos) or satellite (Landsat archives) resources to assess channel behaviour and trajectories. This gap is particularly important in regions of the world where river corridor studies are rare, or where human activities such as damming are an issue (e.g. where channel sensitivity or bedload transport is not monitored). Additionally, recent advances in the digitization of old archives and maps, alongside increasing computational power and the availability of novel geomatic toolboxes, are opening new opportunities to generate vast databases of digital historical information, ready for big-data analysis. More work may be done on derivation of DEMs from stereo-photo pairs. Recent (10–20 years) dynamics could be detected by stereoscopic acquisitions from aircraft or satellite high-resolution images. Some satellites now acquire images at sub-meter resolution in stereoscopic mode (e.g. Pleiades and WorldView) and it would be worth testing their accuracy to explore their utility for Earth surface process monitoring. Finally, we might also question whether, after almost a decade of methodological development, more efforts could be made to use the existing data and place more collective effort on geomorphic understanding, theory and practice, rather than always seeking technological development.

2 *Merging data sources and scales of analysis* to obtain new information, with careful data quality control and validation. Drone data can, for instance, be used to validate information from satellites. Assessing vegetation growth patterns and health is now possible by combining hyperspectral LiDAR information and age unit layers from aerial photo series. A major challenge in the future is to build a modulable, methodological framework integrating different sensors (optical, hyperspectral, LiDAR, SAR, etc.), as well as different spatial (from local to regional) and temporal (daily to annual or greater) approaches. We will need to combine the strengths of each sensor and approach to improve understanding of channel trajectories and behaviour. Traditional measurements (such as stream gauging measurements, width/depth ratios, hydraulic scaling laws) are not obsolete but – quite the contrary – are increasingly indispensable to validate, integrate and generalize RS-based characterization and assessments. More data with higher resolution does not necessarily mean more knowledge. A key challenge and a goal for future river science will be to translate information into knowledge and to critically consider the data quality, metadata and resolution accuracy.

3 *Accessing high temporal resolution RS* information to provide input for water policy. Considerable efforts have been made to characterize the status of rivers, but only a few studies have focused on the changes of river status through time. Monitoring these changes is crucial in understanding channel responses to management actions. Obtaining

bottom-up feedback on the potential success of implemented measures from RS is a real issue in river restoration. Similarly, top-down strategies can be also based on high temporal resolution RS. Combining LiDAR data at regional scales should soon provide inter-annual information (e.g. in Belgium, Switzerland or Denmark) to detect major changes in channel geometry as well as riparian vegetation and identify the most critical reaches, and to design a planning strategy to target actions.

4 *Implementing large-scale models and upscaling catchment characterization to continental or global scales.* We are at the beginning of large/network scale modelling. In the future, river scientists should invest efforts to generate consistent hydrological, morphological and biotic datasets at global scales, working with local, national and international environmental agencies/institutions to characterize river status and develop model frameworks capable of tackling the network scale at which most fluvial processes operate. Some of the key challenges are: to integrate the sediment cascade, supply, transfer and functional connectivity; to combine riparian vegetation recruitment, growth and even diversity; and to quantify channel evolution, including shifting, incision and aggradation. Biogeomorphic diagnostics that use RS to detect differences in health conditions (and explore potential links with stationary conditions, such as water resource availability) should soon be possible. Sediment or wood budgeting is expected to relate to human pressures and land use changes at these large scales. With new resources available, RS is becoming a key technology for monitoring river trajectories and scenarios of change alongside process-based models.

5 *Developing real-time monitoring from ground sensors.* Real-time tools and early-warning systems are increasingly available for monitoring wood flux, bank retreat, sediment transport or hydro-meteorological extreme events. Discharge is already available online in real time. In the future, it is conceivable that websites will provide real-time monitoring of in-channel wood flux, potentially with alerts based on threshold values, as is already the case with water discharge gauging stations or debris-flow hazards in steep slope torrents. Similar systems might be developed for bedload transport with geophones, hydrophones or seismographs.

6 *Exploring new knowledge frontiers that are still a challenge for RS.* Accessing underwater environments remains a key challenge, notably when monitoring channel responses to restoration and aquatic habitat improvement. The main challenge for surficial grain size mapping in rivers remains the characterization of submerged areas, for which we still lack efficient RS solutions. Bathymetry is still challenging for many rivers and it is not clear when it is appropriate to collect RS bathymetric data. Another critical challenge is the investigation of the subsurface sedimentology of river channels, notably the subsurface grain size for which geophysical solutions are still lacking to obtain reliable grain size distribution. Bank material characterization, floodplain geomorphic units and sediment supply are all examples of relevant river components that cannot be easily assessed by RS, even with semi-automated procedures.

RS also still fails to capture key information on rapid phenomena such as the changes and bedload transport that occur in river channels during floods (high-frequency monitoring). Many RS techniques allow extracting 'snapshots' of riverine landscapes, which can then be compared to analyse net changes (i.e. integrating changes during the period between snapshots). Two snapshots of a given landscape might look the same even though the channel has experienced considerable change during the period between snapshots (e.g. compensation). For example, how does a channel or the bed material adjust during a competent flood event? Fieldwork will remain the only feasible method to generate this type of information in the near future. However, this issue might be solved with new emerging ground sensors (which are also RS) rather than classic airborne imagery. We expect a new step of knowledge production to emerge from this ground sensor technology – notably in terms of process understanding at high temporal resolution – relying on the creativity of researchers to adapt these technologies to solve geomorphic questions.

A new era is also emerging in this domain with Big Earth Data. It seems we are just at the beginning of this new period. Fluvial geomorphologists do not really use Big Data yet. There are very few deep learning papers in the river literature because the data are not available. This is especially true with VHR airborne data, where there are no papers on multiple catchments. River scientists still lack a shared global infrastructure to compile and organize data collectively. This is a new avenue for fluvial geomorphologists, and satellite archives are one of the key resources suitable for a Big Data approach.

7 *Developing long-term integrative science observatories* within which RS data are shared, managed and archived. Compiling data on river basins is critical to validate modelling studies and to develop simulations and scenarios. Field campaigns (such as grain size characterization, sediment sources identification, sediment transport monitoring) and river diagnosis (such as multi-temporal aerial photo series) take time, and the processed data are often lost even though subsequent projects could build on these efforts. Archiving long-term data is also critical for practitioners who may access scenarios of change and incorporate them into policy strategies. There is also a clear need to share efforts in knowledge production. Some river scientists must specialise in data acquisition (i.e. data collectors), which is a research task in itself. There are new opportunities to acquire original data at unprecedented scales (i.e. produce repeated near real-time facsimiles of the landscape features) and this implies learning new techniques, designing new sampling and post-processing strategies taking into account data precision, accuracy and different sources of errors. These tasks are time-consuming and sometimes require a never-ending learning process due to the continuous advances in terms of sensors, platforms and software. Peer-reviewed journals must provide space for such methodological research, even if they do not always reach geomorphic answers because practical tests, experiments, descriptions of new techniques are needed to inject new tools and data in the research domain. The geomorphology community must organise itself to support complementary research and engineering, sharing the geomorphic data and tools, and not only methodological developments. Research teams must thus work with methodologists and thematicians. A network strategy can also be necessary when experts cannot be present on a local academic site.

8 *Sharing data and processing tools online.* River science requires collective efforts to improve access to data, geoprocessing tools and algorithms. Building a geomorphological repository of tools and data for monitoring/benchmarking fluvial change, as well as associated literature and tutorials, is urgent to accelerate research and uptake of these tools within the community. Data and

tools can be shared among scientists and practitioners, as both would benefit. Data sharing can induce both bottom-up and top-down strategies: practitioners can provide local data (bottom-up) to implement basin-scale or national-scale tools and use these tools to better contextualize their own catchments within the large-scale framework in term of river status, functionality or responsiveness (top-down). Collecting and managing these data is a long-term investment, which can be enhanced by collaborating with local institutions in charge of data management. Existing archives can be used to characterize large-scale historical trajectories and then advance our capacity to predict future change. Participatory approaches and citizen science are also a key future avenue to obtain information on channel geometry, status and attributes (e.g. grain size), for quality control or validation and for knowledge transfer.

9 *Using RS to re-explore theories.* Many concepts that were developed in the 20th century using small datasets can now be quantified and tested systematically using RS over much larger scales and at greater temporal resolutions than ever before. RS generates new opportunities to disentangle and quantify the role of natural and anthropogenic drivers in shaping river systems, rank them in terms of impact, identify the mosaics of riverscape conditions, better understand the timescales of adjustment and lag times, generate conclusions and assess their range of applicability. Increasingly, it is becoming possible to monitor short-term river trajectories consistently at local, basin, regional or even national scales and to predict future trajectories of change. These advances allow us to test concepts such as river sensitivity (which has been so far introduced mostly theoretically in science and management; Fryirs, 2017), or resilience of river channels to human disturbances, and assess their contextual applications. Large-scale data can also be used in retrospective hydraulic modelling to assess past changes in channel geometry, morphodynamics, sensitivity to changes and bedload transport. Real-time ground monitoring also allows us to better understand the processes at work and reconsider physical drivers to improve modelling approaches. The time has come to translate our requests for more data (which are now partially satisfied) into efforts to use existing data to review and advance the basic concepts and theories at the core of fluvial geomorphology.

10 *Promoting a critical approach to RS practices.* It is clear that some of the 'emergent' remote-sensing techniques are no longer new. These techniques are already available for the community, with clear workflows and freely available tools, and, consequently, we need to use them for specific objectives, avoiding further methodological developments and improving the knowledge we have in terms of understanding how rivers work (both natural and disturbed systems) and their future trajectories. Furthermore, the intensive use of RS tools to characterize environmental processes is not neutral: depending on the context and the issue, these methods may exclude certain stakeholders, limit the understanding of phenomena and/or generate controversial data. Thus the use of RS tools needs to be combined with a critical understanding of their sociological and cultural effects, and complementary approaches to counterbalance any potential negative effects. Thus interdisciplinary scientific teams are required to generate integrative river science. Collaborative engagement and co-development of decision-support tools are required to identify solutions to problems faced by specific stakeholders.

Conclusions

Research in RS is essential to address one of the major challenges of the Anthropocene: understanding and managing the relationship between society and the environment. Field data alone are insufficient to tackle complex geomorphic questions, and the reverse (RS without field data for validation and field observation) is also true. While geomorphologists still need to spend time in the field observing the complexity of processes and landforms, geomorphic understanding can also emerge from image observations. RS resources provide much greater insight into the spatial variability of channel forms and processes than ever before – from the scale of the cross-section to that of entire river networks. However, even with the enhanced availability of data, river scientists still need to develop appropriate scientific questions, ground-truth measurements at relevant space and time scales, and interpret the data.

RS is no longer only a scientific tool; it is a set of data and techniques for informing river managers at local to basin scales. River scientists need to move beyond simple methodological development (eureka, it works!) by sharing tools, transferring knowledge and developing a critical understanding of where, how and when methods can be accurately incorporated into applied geomorphology. RS can be used to help implement and monitor management measures, identify criticalities, tipping points, future trajectories, pressures and their effects, better than in the past. Merging field observations with RS information will allow us to understand rivers in the Anthropocene and identify the best management scenarios for their (and our) future.

Data availability statement

This is a review paper, not concerned with data availability.

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