Remotely Sensed Rivers in the Anthropocene: State of the Art and Prospects

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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.

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

1. 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 spatio-temporal 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) and Wohl (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 & Fryirs, 2018). The concept also suggests that fluvial systems are now socio-ecological 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 & 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, 2014; 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 & Rinaldi, 2003; Brierley & Fryirs, 2008; Dufour & 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), impulsive (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 & Piégay, 2009). A temporal analysis of past river processes and natural inheritance is necessary to understand present river conditions, sensitivity and resilience (Brierley & 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 remote sensing 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 remote sensing 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-, 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 Remote Sensing in Carbonneau & Piégay (2012) or more recent publications (Gilvear et al., 2016; Entwistle et al., 2018; Tomsett & Leyland, 2019). RS can help understand 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. Remote sensing 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, etc.) and RS data validation is usually based on intensive field surveys (See Carbonneau & Piégay, 2012; Bizzi et al., 2016). In summary, remote sensing 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 early review on the application of remote sensing in fluvial geomorphology highlighted that remote sensing is often the only way to obtain an "overall picture" of river functioning at large scales. This overall picture is fundamental to understand 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 remote sensing.

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 summarise insights and challenges for new research.

Figure 1. General framework of geomorphic studies: diagnosis and project appraisal, top-down and bottom-up strategies (source: Piégay et al. 2016, chapter 22)

2. Remote sensing to explore past conditions within the Anthropocene

2.1. Data and methodological framework to diagnose river changes

Aerial photography

Reconstructing river trajectories requires the use of historical data, and especially remote sensing information (Grabowski & Gurnell, 2016). Early studies mostly relied on the use of oblique and vertical aerial photography in the visible domain. The use of remote sensing to explore past conditions starts with the advent of aerial photography around the 1930s, with mainly black and white images before the 1970s (Gilvear & 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 remote sensing 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 (Hookes, 2003; Alber & 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 & 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 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; ca 3 millions 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

Remote sensing 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 & Montgomery 2001, Slater & Singer 2013, Phillips & Jerolmack 2016; Pfeiffer et al., 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 & Watson, 1997; Pinter & 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).

2.2. Reach-scale changes

Classical approach from airborne images

A classic approach to analyze reach-scale channel adjustments over multiple kilometres is to compile historical aerial photographs. Series of photographs are selected at least every ten years, depending on the availability of archived photos and flood dates, and integrated in a GIS environment to extract geomorphic variables, e.g. active channel width or sinuosity, gravel bar area (Gilvear et al., 2000; Ollero, 2010; Michalkova 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 analyzing the temporal series of historical remote sensing data, we can detect discontinuities in the spatio-temporal trajectories of rivers. Homogeneous sub-reaches in terms of magnitude of change can be statistically delineated using tests for stationarity (Alber & 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 & Ferreira, 2005; Dufour et al., 2007; Kondolf et al., 2007; Cadol et al., 2010; 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. (*in review*) 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 sections 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 twelve 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 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 remote sensing 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 with 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., 2019).

Figure 2. Temporal evolution of surface areas through time based on a series of aerial photographs: (A) example of the terrestrialisation of the natural (dashed line) and artificial (thick line) abandoned channels of the Rhône River – Grange Ecrasée is the only one case of expansion right after cut-off and then shrinking (Source: Figure 1, Dépret et al. 2017, Geomorphology) (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

Vertical information can also be derived directly from archived aerial photographs using digital photogrammetry (Lane, 2000; Gilvear & Bryant, 2016; Bakker & 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 (TS). 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 & 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 & Lane, 2017). For example, it has been demonstrated that SfM data processing of historical air 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 remote sensing) is often used to better contextualise reach-scale changes within a catchment and landscape context. For example, Ziliani and Surian (2012) 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 vs. large-scale drivers in the evolutionary trajectory of channel morphology along the nearly-natural Tagliamento river (north-western Italy).

2.3. 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 km of river length). Two strategies are usually implemented: i) assessing inter-reach differences at the network scale to infer controlling factors, 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 & 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 which can be compared in space and time (Belletti et al., 2015). The approach mainly consists in combining present remote sensing 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-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 which 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 twenty mountain streams (channel narrowing, bed degradation and armouring) were largely controlled by watershed morphometry and land use, permitting to better understand 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 ten years thanks to a better temporal and spatial resolution in remote sensing 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) (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 19^{th} century and for which automatic vectorization is possible (Horacio et al., on line).

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 (source: Figure 12, Bizzi et al., 2018 in ESPL)

3. Remote sensing to identify patterns and acting processes

3.1 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 1).

Ground-based and close-range surveying techniques

Field-based approaches in fluvial geomorphology increasingly use terrestrial remote sensing to survey the topography and to measure the fluxes of water, sediment or wood passing through a river section. For example, Terrestrial Laser Scanning (TLS) is now commonly employed to produce dense 3D point clouds of river channels (e.g. Milan et al., 2007; Heritage & 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 & Piégay, 2012), seismic sensors (Burtin et al., 2016) or active 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 Vehicle (UAV) 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 get 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 km 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, Structure from Motion (SfM) photogrammetry has largely resolved the issue of image orthorectification and Digital Elevation Model (DEM) production (James & 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 & 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 cm 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 € (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, even RFID tracking technology (Cassel et al., *in review*).

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 recognise that SfM-photogrammetry, whilst still strongly rooted in photogrammetry, requires its own expertise. The best 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 recognised 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 is still a critical requirement 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 multi-spectral satellite images (around the late 1970s for the Landsat TM), satellites provide 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 both in visible, infrared and radar domains (e.g. Spada et al., 2018 who combine data from the CORONA, Landsat and Sentinel-2 missions) that are publicly-accessible and provide high spatial resolution (10 to 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 (sub-weekly acquisition), colleting 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. Remote sensing 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 this data to pose specific research questions to advance fluvial geomorphology scientific understanding.

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) Kristell Michel; B) Mathieu Cassel; C) Baptiste Marteau and D) Philippe Grandjean)

3.2. 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 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 & Church, 1998; Guerit et al., 2014). Collecting data about surficial GSD has been for a long time only 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 & 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., 2002; Graham et al., 2005 a and b; Detert & 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 & Masselink, 2009; Buscombe et al., 2010). Chardon et al. (*in review*) tested the automatic Buscombe procedure on underwater images and showed solar lighting conditions and particles 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 & Milan, 2009; Brasington et al., 2012; Vázquez-Tarrío et al., 2017). Only 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 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 & Fuller, 2009; Heritage & 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 which 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 remote sensing 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 to 49 points/m^2, mean distance between points of 0.08 m to 0.09 m) and the laser spot size fairly low (0.12 m at NADIR; see Chardon et al., *in review*), comparatively to observed grain sizes, allowing to cover areas much larger than with drones.

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 (Source: Carbonneau et al., 2005, Figure 5.).

The study of longitudinal grain shape evolution helps understand 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 get 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 been also proposed to estimate roundness of individual particles using 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 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.

Figure 6. (A) Evolutions 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 values 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 percentiles values. White circles represent median values. (B) Example of picture of angular pebbles taken for roundness analysis. (Source: Cassel et al., 2018, Figure 11 and Figure 3).

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 remote sensing. 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; Fuerer et al., 2008; Lane et al. 2010), or a 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., 2015). 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 remote sensing with intensive measurements from boat are 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 & Brierley (2012) define these landforms as the "building blocks" of the fluvial mosaic, but other terms have been proposed, like geomorphic units, hydraulic units, physical habitats, meso-habitats or biotopes (Milan et al., 2010; Wyrick et al., 2014; Wheaton et al., 2015; Belletti et al., 2017). Some recent works combine multisource remote sensing 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 in 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. (*in revision*) developed a novel approach dubbed 'CNN-Supervised Classification' which uses a pre-trained convolutional neural network 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. (*in revision*) 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, the last 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 & Dietrich, 2016). The ability to identify vegetation composition, including at species scale, and to describe vegetation structure has greatly increased (Kaneko & 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 & 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). The ability to identify vegetation composition, including at species scale, has been also greatly increased with the development of hyperspatial (Kaneko & 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 remote sensing 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 & Buffin-Bélanger, 2010; Tonon et al., 2014).

Figure 7. Riparian genuses map obtained from LiDAR data and tree morphological patterns (Sélune River, western France). Tree crown morphology and internal structure indicators were computed from the 3D points 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 3 genuses to 50% for 8 genuses. With 8 genuses, the identification remains a challenge as for one tree crown predicted pixels can be mixed (Source: Ba et al., 2019)

In recent decades, important efforts have been made for network-scale mapping of fluvial environments (Alber & 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 LiDAR DEM (Demarchi et al., 2017). 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.

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). (Source: Demarchi et al. 2016 Figure 5)

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 60S and 60N extracted using the SRTM Water Body Database (Yamazaki et al., 2014). Considerable advances may be achieved by using global archives to interrogate or predict 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 & 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). 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 been generated also (Weissteiner et al., 2016).

3.3. Fluvial processes: from decadal landform changes to real time observations

The notable advances in fluvial remote sensing 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 have been reported (Lane et al., 1994; Lane et al., 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 km 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 remote sensing 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), channel response to restoration projects (Campana et al., 2014; Heckmann et al., 2017) (Figure 9).

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 (source: Brousse et al, online); the combination of HR topographic differencing before and after a 5-yr flood and bedload tracing successfully allow to detect the propagation of the artificially-induced sediment wave, with a front located at 2.5 km from the dam

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 (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, 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 been also 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 validate a wood budget for the reach upstream of the camera (Figure 10A&B). 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 the last years and will continue in the future.

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 April 10–13, 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, US) at different times (t), h: water depth and z: wood flow depth; d_w: wood piece diameter; k: coefficient >1 (Modified from Ruiz-Villanueva et al., 2019).

Ground-based remote sensing techniques for the indirect monitoring of bedload transport are also in an active phase of development. Seismic sensors like impact sensors, geophones or 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; Downs et al., 2016; Burtin et al., 2016; Roth et al., 2016). Their deployment in the 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, like hydrophones (Belleudy et al., 2010; Geay et al., 2017). Although reliable estimates of bedload flux with seismic and acoustic sensors still implies 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, 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).

Table 1 – 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 & Bookhagen, 2019
		X			2.5 km	yes	Aerial photos (RGB)	Vázquez-Tarrío et al., 2017
		X			Reach Scale	no	UAV/SfM	Carbonneau et al. 2018
	X		X			no	Ground photos, airborne LiDAR	Chardon et al.,*in review*
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 & 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, J. & Vacková, 2018
			X			no	Airborne LiDAR	Wheaton et al., 2015
			X		Drôme network (1640 km2)	no	Orthophotos (RGB and NIR)	Bertrand et al. 2013 a
			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 (21000 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 a RGB camera	Sanhueza et al., 2018
		X						
			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 a 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
		X			Several reaches along the Blanco River	no	UAV/SfM with a 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, 80km	no	RGB camera	Carbonneau et al., 2006
Water, sediment and wood fluxes								
Water level		X			Ridracoli reservoir	yes	UAV with a 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 (<1km²)	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., *in review*
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 0.35km²)	yes	Ground images (RGB)	Benacchio et al., 2017
	X		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

4. 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., 2013 a and 2013 b), and increasingly process-based models. Remote sensing technology is moving toward the possibility to map 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 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 remote sensing 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 NDVI) 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.

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 28m^3/s. From Ruiz-Villanueva et al., 2017.

Catchment-scale models

Until a few years ago, catchment scale models were limited by the lack of suitable datasets, but are now flourishing research area which is providing valuable evidence to support the management and planning of river systems. Catchment-scale models have become feasible due 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 & 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 & Schwanghart, 2013; Czuba and Foufoula-Georgiou, 2014; Heckmann et al., 2015 Parker et al., 2015; Czuba, 2018; Heckmann et al. 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).

Figure 12. Examples of plots obtained from CASCADE toolbox (source: Tangi et al, 2019). The tool allows analysing various properties of sediment connectivity in an interactive manner. Panel a shows the total sediment transported in Kg/s in the network. b visualizes patterns of deposition for a single sediment class out of the 18 considered in the model (in this case boulders/cobbles). c shows the changes in total sediment transport caused by the removal of one dam and two external sediment flows. d shows an 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.

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 & Meleason, 2003; Mazzorana et al., 2009; Ruiz-Villanueva et al., 2014 a; 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).

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).

5. 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 remote sensing 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 remote sensing technology generally increases rapidly with increasing resolution, along with associated costs in terms of data handling and processing and the technical skills required to analyze 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 € (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 operations for the mass consumer market means that these low-cost airborne platforms are capable of automated flight, have single-phase, non-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 meters 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 will be composed of 4 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. 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 GRDB and the World Meteorological Organisation'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).

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). The inset shows the number and proportion of river reaches per dominant pressure indicator at the global scale. (Source: Grill et al., 2019; Figure 2)

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 analyze 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.

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 like 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 manipulating remote sensing data, correcting and rescaling satellite imagery, or for analyzing 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, or 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. (*in revision*) 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 (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 & 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) or the RVR Meander toolbox (Abad & 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 centerline 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., subm.) used across networks, allow to categorize 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.

Figure 14. Example of tools/interfaces available online to measure characters of fluvial corridors : A) The Fluvial Corridor Toolbox – FCT - within the ArcGIS Arc Toolbox (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 the Geomorphic Change Detection software (http://gcd.riverscapes.xyz/) (Wheaton et al., 2010a); and 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) (Detert et Weitbrecht, 2012)

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 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 & 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 which provide a suite of hydrological standard specifications to BRIdging Services Information and Data for Europe (BRISEIDE) project to visualize, manage and process geospatial resources useful for hydrological model development. Google Earth or NASA WorldWind also offer capabilities to visualize spatio-temporal 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 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.

6. **Prospects for the remote sensing of Anthropocene rivers**

Remote sensing 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 utilise 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 are thus 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 include:

1) <u>Exploring existing data more deeply</u> 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 are not monitored). Additionally, recent advances in the digitisation 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 airplane or satellite high resolution images. Some satellites acquire now at sub-meter resolution in stereoscopic mode (e.g., Pleiades and WorldView) and it would be worth testing their accuracy to explore what kind of earth surface process monitoring they can be exploited for. Finally, we might also question if after almost a decade of methodological development, more efforts could be made to use the existing new 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 mean necessarily 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 to understand 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 planning strategy to target actions.

4) Implementing large scale models and upscaling catchment characterisation 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. Bio-geomorphic 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 with 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 remote sensing 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 which 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). Much of the RS techniques allow extracting ‘snapshots’ of riverine landscapes These can be compared to analyse net changes (i.e. integrate changes during the period between snapshots). Two snapshots of a given landscape might look the same even though the channel has experience 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? Field work 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 almost no deep learning papers in the river literature because the data is 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 organise 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. Here is also a clear need to share efforts in knowledge production. Some river scientists must specialise in data acquisition (i.e. data collectors). It 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. he 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 join 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 contextualise 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 reexplore 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 time scales 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 this 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 bexclude 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.

6. Conclusions

Research in remote sensing 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 is insufficient to tackle complex geomorphic questions, and the reverse (remote sensing 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. Remote sensing 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.

Remote sensing 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 critical understanding of where, how and when methods can be accurately incorporated in applied geomorphology. Remote sensing 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.

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8. References

Abad, J. D., & Garcia, M. H. (2006). RVR Meander: A toolbox for re-meandering of channelized streams. *Computers & Geosciences, 32(1)*, 92–101.

Abalharth, M., Hassan, M. A., Klinkenberg, B., Leung, V., & McCleary, R. (2015). Using LiDAR to characterize logjams in lowland rivers. *Geomorphology*, *246*, 531-541.

Adams J. 1979. Gravel size analysis from photographs. Journal of the Hydraulics Division of the American Society of Civil Engineers 105: 1247-1255Aguiar, F. C., & Ferreira, M. T. (2005). Human-disturbed landscapes: effects on composition and integrity of riparian woody vegetation in the Tagus River basin, Portugal. *Environmental Conservation*, *32*(1), 30-41.

Alber, A., & Piégay, H. (2011). Spatial disaggregation and aggregation procedures for characterizing fluvial features at the network-scale: Application to the Rhône basin (France). *Geomorphology*, *125*(3), 343-360.

Alber, A., & Piégay, H. (2017). Characterizing and modelling river channel migration rates at a regional scale: Case study of south-east France. *Journal of environmental management*, *202*, 479-493.

Allen, G. H., & Pavelsky, T. M. (2018). Global extent of rivers and streams. *Science*, *361*(6402), 585-588. https://doi.org/10.1126/science.aat0636.

Allred, T. M., & Schmidt, J. C. (1999). Channel narrowing by vertical accretion along the Green River near Green River, Utah. *Geological Society of America Bulletin*, *111*(12), 1757-1772. DOI: 10.1130/0016-7606(1999)111<1757.

Amatulli, G., Domisch, S., Tuanmu, M. N., Parmentier, B., Ranipeta, A., Malczyk, J., & Jetz, W. (2018). A suite of global, cross-scale topographic variables for environmental and biodiversity modeling. *Scientific data*, *5*, 180040. http://www.earthenv.org/topography. https://doi.org/10.1038/sdata.2018.40.

Anderson, S. W. (2019). Uncertainty in quantitative analyses of topographic change: error propagation and the role of thresholding. *Earth Surface Processes and Landforms*, *44*, 1015-1033.

Antonarakis, A. S., Richards, K. S., Brasington, J., Bithell, M., & Muller, E. (2008). Retrieval of vegetative fluid resistance terms for rigid stems using airborne lidar. *Journal of Geophysical Research: Biogeosciences*, *113*(G2).

Antoniazza, G., Bakker, M., Lane, S. (2019). Revisiting the morphological method in two-dimensions to quantify bed-material transport in braided rivers. Ear. Surf. Proc. Land. Online Early View.

Archer, L., Neal, J. C., Bates, P. D., & House, J. I. (2018). Comparing TanDEM-X Data With Frequently Used DEMs for Flood Inundation Modeling. *Water Resources Research*, *54*(12), 10-205.

Arnaud, F., Piégay, H., Schmitt, L., Rollet, A. J., Ferrier, V., & Béal, D. (2015). Historical geomorphic analysis (1932–2011) of a by-passed river reach in process-based restoration perspectives: The Old Rhine downstream of the Kembs diversion dam (France, Germany). *Geomorphology*, *236*, 163-177.

Atha, J. B. (2014). Identification of fluvial wood using Google Earth. *River research and applications*, *30*(7), 857-864. https://doi.org/10.1002/rra.2683

Atha, J. B., & Dietrich, J. T. (2016). Detecting fluvial wood in forested watersheds using LiDAR Data: a methodological assessment. *River Research and Applications*, *32*(7), 1587-1596. doi:10.1002/rra.2989

Ba, A., Laslier, M., Dufour, S., & Hubert-Moy, L. (2019). Riparian trees genuses identification based on leaf-on/leaf-off airborne laser scanner data and machine learning classifiers in western France. *International Journal of Remote Sensing*. https://doi.org/10.1080/01431161.2019.1674457

Bailly J-S, Le Coarer Y, Languille P, Stigermark C-J, Allouis T. (2010). Geostatistical estimations of bathymetric LiDAR errors on rivers. Earth Surface Processes and Landforms, **35**, 1199–1210.

Bakker, M., & Lane, S. N. (2017). Archival photogrammetric analysis of river–floodplain systems using Structure from Motion (SfM) methods. *Earth Surface Processes and Landforms*, *42*(8), 1274-1286. doi:10.1002/esp.4085

Barker, D. M., Lawler, D. M., Knight, D. W., Morris, D. G., Davies, H. N., & Stewart, E. J. (2009). Longitudinal distributions of river flood power: the combined automated flood, elevation and stream power (CAFES) methodology. *Earth Surface Processes and Landforms*, *34*(2), 280-290.

Bauer, M., Harzer, R., Strobl, K., & Kollmann, J. (2018). Resilience of riparian vegetation after restoration measures on River Inn. *River research and applications*, *34*(5), 451-460.

Bedell, E., Leslie, M., Fankhauser, K., Burnett, J., Wing, M. G., & Thomas, E. A. (2017). Unmanned aerial vehicle-based structure from motion biomass inventory estimates. *Journal of Applied Remote Sensing*, *11*(2), 026026.

Belletti, B., Dufour, S., & Piégay, H. (2014). Regional assessment of the multi-decadal changes in braided riverscapes following large floods (Example of 12 reaches in South East of France). *Advances in Geosciences*, *37*, 57-71.

Belletti, B., Dufour, S., & Piégay, H. (2015). What is the relative effect of space and time to explain the braided river width and island patterns at a regional scale?. *River research and applications*, *31*(1), 1-15.

Belletti, B., Rinaldi, M., Bussettini, M., Comiti, F., Gurnell, A. M., Mao, L., ... & Vezza, P. (2017). Characterising physical habitats and fluvial hydromorphology: A new system for the survey and classification of river geomorphic units. *Geomorphology*, *283*, 143-157. https://doi.org/10.1016/j.geomorph.2017.01.032

Benacchio, V., Piégay, H., Buffin-Bélanger, T., & Vaudor, L. (2017). A new methodology for monitoring wood fluxes in rivers using a ground camera: Potential and limits. *Geomorphology*, *279*, 44-58. doi:10.1016/j.geomorph.2016.07.019

Benjankar, R., Burke, M., Yager, E., Tonina, D., Egger, G., Rood, S. B., & Merz, N. (2014). Development of a spatially-distributed hydroecological model to simulate cottonwood seedling recruitment along rivers. *Journal of environmental management*, *145*, 277-288.

Bertoldi, W., Gurnell, A. M., & Drake, N. A. (2011). The topographic signature of vegetation development along a braided river: results of a combined analysis of airborne lidar, color air photographs, and ground measurements. *Water Resources Research*, *47*(6).https://doi.org/10.1029/2010WR010319.

Bertoldi, W., Piégay, H., Buffin-Bélanger, T., Graham, D., Rice, S. (2012). Applications of Close-range Imagery in River Research. In: Carbonneau, P.E., & Piégay, H. (Eds), *Fluvial Remote Sensing for Science and Management*, Chichester, UK: John Wiley & Sons, Ltd,

Bertoldi, W., Siviglia, A., Tettamanti, S., Toffolon, M., Vetsch, D., & Francalanci, S. (2014). Modeling vegetation controls on fluvial morphological trajectories. *Geophysical Research Letters*, *41*(20), 7167-7175.

Bertrand, M., Piégay, H., Pont, D., Liébault, F., & Sauquet, E. (2013 a). Sensitivity analysis of environmental changes associated with riverscape evolutions following sediment reintroduction:

geomatic approach on the Drôme River network, France. *International journal of river basin management*, *11*(1), 19-32.

Bertrand, M., Liébault, F., & Piégay, H. (2013 b). Debris-flow susceptibility of upland catchments. *Natural Hazards*, *67*(2), 497-511.

Bertrand, M., Liébault, F., & Piégay, H. (2017). Regional Scale Mapping of Debris-Flow Susceptibility in the Southern French Alps. *Journal of Alpine Research| Revue de géographie alpine*, (105-4).

Bertrand, M., & Liébault, F. (2019). Active channel width as a proxy of sediment supply from mining sites in New Caledonia. *Earth Surface Processes and Landforms*, *44*(1), 67-76.

Biedenharn, D. S., & Watson, C. C. (1997). Stage adjustment in the lower Mississippi River, USA. *Regulated Rivers: Research & Management: An International Journal Devoted to River Research and Management*, *13*(6), 517-536.

Bird, S., Hogan, D., & Schwab, J. (2010). Photogrammetric monitoring of small streams under a riparian forest canopy. *Earth Surface Processes and Landforms*, *35*(8), 952-970.

Bizzi, S., & Lerner, D. N. (2015). The use of stream power as an indicator of channel sensitivity to erosion and deposition processes. *River Research and Applications*, *31*(1), 16-27. DOI: 10.1002/rra.2717

Bizzi, S., L. Demarchi, R. C. Grabowski, C. J. Weissteiner, e W. Van de Bund. (2016). The Use of Remote Sensing to Characterise Hydromorphological Properties of European Rivers. *Aquatic Sciences* 78(1), 57–70. https://doi.org/10.1007/s00027-015-0430-7

Bizzi, S., Piégay, H., Demarchi, L., Van de Bund, W., Weissteiner, C. J., & Gob, F. (2019). LiDAR-based fluvial remote sensing to assess 50–100-year human-driven channel changes at a regional level: The case of the Piedmont Region, Italy. *Earth Surface Processes and Landforms*, *44*(2), 471-489.

Blaschke, T. (2010). Object based image analysis for remote sensing. *ISPRS journal of photogrammetry and remote sensing*, *65*(1), 2-16. DOI: 10.1016/j.isprsjprs.2009.06.004

Blaschke, T., Hay, G. J., Kelly, M., Lang, S., Hofmann, P., Addink, E., ... & Tiede, D. (2014). Geographic object-based image analysis–towards a new paradigm. *ISPRS journal of photogrammetry and remote sensing*, *87*, 180-191. DOI: 10.1016/j.isprsjprs.2013.09.014

Blench, T. (1969). *Mobile-bed fluviology: a regime theory treatment of rivers for engineers and hydrologists*. University of Alberta Press: Edmonton.

Boivin, M., Buffin-Bélanger, T., & Piégay, H. (2017). Estimation of large wood budgets in a watershed and river corridor at interdecadal to interannual scales in a cold-temperate fluvial system. *Earth Surface Processes and Landforms*, *42*(13), 2199-2213.

Bonin, L., Proulx, R., & Rheault, G. (2014). A digital photography protocol for the rapid assessment of herbaceous communities in riparian buffers. *Riparian Ecology and Conservation*, *2*(1), 35-44.

Bracken, L. J., Turnbull, L., Wainwright, J., & Bogaart, P. (2015). Sediment connectivity: a framework for understanding sediment transfer at multiple scales. *Earth Surface Processes and Landforms*, *40*(2), 177-188. DOI: 10.1002/esp.3635

Brasington, J., Vericat, D., & Rychkov, I. (2012). Modeling river bed morphology, roughness, and surface sedimentology using high resolution terrestrial laser scanning. *Water Resources Research*, *48*(11).

Brierley, G. J., & Fryirs, K. A. (2005). *Geomorphology and River Management: Applications of the River Styles Framework*. Malden, MA: Blackwell Publishing. https://doi.org/10.1002/9780470751367.

Brierley, G.J., & Fryirs, K.A. (2008). *River futures: an integrative scientific approach to river repair*. Island press

Brierley, G., Fryirs, K., Cullum, C., Tadaki, M., Huang, H. Q., & Blue, B. (2013). Reading the landscape: Integrating the theory and practice of geomorphology to develop place-based understandings of river systems. *Progress in Physical Geography*, *37*(5), 601-621. DOI: 10.1177/0309133313490007

Brousse, G., Arnaud-Fassetta, G., Liébault, F., Bertrand, M., Melun, G., Loire, R., Malavoi, J.R., Fantino, G., Borgniet, L., *in review*. Monitoring of sediment replenishment in a large gravel-bed river : the case of the Saint-Sauveur dam in the Buëch River (Southern Alps, France). *River Research and Applications*.

Brown, A. G., Tooth, S., Bullard, J. E., Thomas, D. S., Chiverrell, R. C., Plater, A. J., ... & Wainwright, J. (2017). The geomorphology of the Anthropocene: emergence, status and implications. *Earth Surface Processes and Landforms*, *42*(1), 71-90.

Brown, A. G., Lespez, L., Sear, D. A., Macaire, J. J., Houben, P., Klimek, K., ... & Pears, B. (2018). Natural vs anthropogenic streams in Europe: history, ecology and implications for restoration, river-rewilding and riverine ecosystem services. *Earth-science reviews*, *180*, 185-205.

Burtin A, Cattin R, Bollinger L, Vergne J, Steer P, Robert A, Findling N, Tiberi C. 2011. Towards the hydrologic and bed load monitoring from high-frequency seismic noise in a braided river: The "torrent de St Pierre", French Alps. Journal of Hydrology **408**: 43-53

Burtin, A., Hovius, N., & Turowski, J. M. (2016). Seismic monitoring of torrential and fluvial processes. *Earth Surface Dynamics*, *4*(2), 285-307. DOI: 10.5194/esurf-4-285-2016.

Buscombe, D. (2008). Estimation of grain-size distributions and associated parameters from digital images of sediment. *Sedimentary Geology*, *210*(1-2), 1-10. DOI: 10.1016/j.sedgeo.2008.06.007

Buscombe, D., & Masselink, G. (2009). Grain-size information from the statistical properties of digital images of sediment. *Sedimentology*, *56*(2), 421-438. DOI: 10.1111/j.1365-3091.2008.00977.x

Buscombe, D., Rubin, D. M., & Warrick, J. A. (2010). A universal approximation of grain size from images of noncohesive sediment. *Journal of Geophysical Research: Earth Surface*, *115*(F2). DOI: 10.1029/2009JF001477

Buscombe, D., & Ritchie, A. (2018). Landscape classification with deep neural networks. *Geosciences*, *8*(7), 244. DOI: 10.3390/geosciences8070244

Butler, J. B., Lane, S. N., & Chandler, J. H. (2001). Automated extraction of grain-size data from gravel surfaces using digital image processing. *Journal of Hydraulic Research*, *39*(5), 519-529.

Bywater-Reyes, S., Wilcox, A. C., & Diehl, R. M. (2017). Multiscale influence of woody riparian vegetation on fluvial topography quantified with ground-based and airborne LiDAR. *Journal of Geophysical Research: Earth Surface*, *122*(6), 1218-1235.

Cadol, D., Rathburn, S. L., & Cooper, D. J. (2011). Aerial photographic analysis of channel narrowing and vegetation expansion in Canyon de Chelly National Monument, Arizona, USA, 1935–2004. *River Research and Applications*, *27*(7), 841-856. http://dx.doi.org/10.1002/rra.1399

Campana, D., Marchese, E., Theule, J. I., & Comiti, F. (2014). Channel degradation and restoration of an Alpine river and related morphological changes. *Geomorphology*, *221*, 230-241.

Carbonneau, P. E., Lane, S. N., & Bergeron, N. E. (2004). Catchment-scale mapping of surface grain size in gravel bed rivers using airborne digital imagery. *Water resources research*, *40*(7).

Carbonneau, P. E., Bergeron, N., & Lane, S. N. (2005). Automated grain size measurements from airborne remote sensing for long profile measurements of fluvial grain sizes. *Water Resources Research*, *41*(11), W11426. DOI: 10.1029/2005WR003994

Carbonneau PE, Lane SN, Bergeron N. (2006). Feature based image processing methods applied to bathymetric measurements from airborne remote sensing in fluvial environments. Earth Surface Processes and Landforms, **31**, 1413–1423.

Carbonneau, P., Fonstad, M. A., Marcus, W. A., & Dugdale, S. J. (2012). Making riverscapes real. *Geomorphology*, *137*(1), 74-86. DOI: 10.1016/j.geomorph.2010.09.030

Carbonneau, P., & Piégay, H. (Eds.). (2012). *Fluvial remote sensing for science and management*, Chichester, UK: John Wiley & Sons, Ltd,

Carbonneau, P. E., & Dietrich, J. T. (2017). Cost‐effective non‐metric photogrammetry from consumer‐grade sUAS: implications for direct georeferencing of structure from motion photogrammetry. *Earth Surface Processes and Landforms*, *42*(3), 473-486.DOI: 10.1002/esp.4012

Carbonneau, P. E., Bizzi, S., & Marchetti, G. (2018). Robotic photosieving from low‐cost multirotor sUAS: a proof‐of‐concept. *Earth Surface Processes and Landforms*, *43*(5), 1160-1166. DOI: 10.1002/esp.4298

Carbonneau, P.E., Dugdale, S.J., Breckon, T.P., Dietrich, J.D., Fonstad, M.A., Miyamoto, H., & Woodget, A.S. (*in revision*). Generalised classification of fluvial scenes with deep learning methods. In review, *Remote Sensing of Environment.*

Carley, J. K., Pasternack, G. B., Wyrick, J. R., Barker, J. R., Bratovich, P. M., Massa, D. A., ... & Johnson, T. R. (2012). Significant decadal channel change 58–67 years post-dam accounting for uncertainty in topographic change detection between contour maps and point cloud models. *Geomorphology*, *179*, 71-88.

Casado, M., Gonzalez, R., Kriechbaumer, T., & Veal, A. (2015). Automated identification of river hydromorphological features using UAV high resolution aerial imagery. *Sensors*, *15*(11), 27969-27989. DOI: 10.3390/s151127969

Cassel, M., Dépret, T., & Piégay, H. (2017). Assessment of a new solution for tracking pebbles in rivers based on active RFID. *Earth Surface Processes and Landforms*, *42*(13), 1938-1951. DOI: 10.1002/esp.4152.

Cassel, M., Piégay, H., Lavé, J., Vaudor, L., Sri, D. H., Budi, S. W., & Lavigne, F. (2018). Evaluating a 2D image-based computerized approach for measuring riverine pebble roundness. *Geomorphology*, *311*, 143-157.https://doi.org/10.1016/j.geomorph.2018.03.020.

Cassel M, Guillaume F., Ludovic B., Kristell M., Perret F., Lejot J., Piégay H. (*accepted*). Comparison of ground-based and UAV a-UHF artificial tracer mobility monitoring protocols on a braided river. Earth Surface Processes and Landforms

Chardon, V., Schmitt, L, Piégay, H., Dimitri, L. (*in review*). Terrestrial photo-sieving and airborne topographic LiDAR to assess bed grain size in large rivers: potentials and limits.

Cavalli, M., Tarolli, P., Marchi, L., Dalla Fontana, G. (2008). The effectiveness of airborne LiDAR data in the recognition of channel-bed morphology. Catena, 73(3), 249-260.

Cavalli, M., Trevisani, S., Comiti, F., Marchi, L. (2013). Geomorphometric assessment of spatial sediment connectivity in small Alpine catchments. *Geomorphology*, 188, 31–41.

Charlton, M.E., Large, A.R., Fuller, I.C. (2003). Application of airborne LiDAR in river environments: the River Coquet, Northumberland, UK. Earth Surface Processes and Landforms, 28(3), 299-306.

Chenorkian, R. (2012). A new tool to overall analyze the interactions between man and his environment, along with their dynamics: the network of Human & Environmental Observatories. Les Observatoires Hommes-Milieux: un nouveau dispositif pour une approche intégrante des interactions environnements-sociétés et de leurs dynamiques. *Sud-Ouest européen. Revue géographique des Pyrénées et du Sud-Ouest*, (33), 3-10.

Cislaghi, A., Rigon, E., Lenzi, M. A., & Bischetti, G. B. (2018). A probabilistic multidimensional approach to quantify large wood recruitment from hillslopes in mountainous-forested catchments. *Geomorphology*, *306*, 108-127.

Clerici, N., Paracchini, M. L., & Maes, J. (2014). Land-cover change dynamics and insights into ecosystem services in European stream riparian zones. *Ecohydrology & Hydrobiology*, *14*(2), 107-120.

Clubb, F. J., Mudd, S. M., Milodowski, D. T., Hurst, M. D., & Slater, L. J. (2014). Objective extraction of channel heads from high-resolution topographic data. *Water Resources Research*, *50*(5), 4283-4304.

Clubb, F. J., Mudd, S. M., Milodowski, D. T., Valters, D. A., Slater, L. J., Hurst, M. D., & Limaye, A. B. (2017). Geomorphometric delineation of floodplains and terraces from objectively defined topographic thresholds. *Earth Surface Dynamics*, *5*(3).

Comiti, F., Da Canal, M., Surian, N., Mao, L., Picco, L., & Lenzi, M. A. (2011). Channel adjustments and vegetation cover dynamics in a large gravel bed river over the last 200 years. *Geomorphology*, *125*(1), 147-159.

CEMS GloFAS (2019), River discharge and related historical data from the Global Flood Awareness System, DOI: 10.24381/cds.a4fdd6b9

Corenblit, D., Tabacchi, E., Steiger, J., Gurnell, A.M. (2007). Reciprocal interactions and adjustments between fluvial landforms and vegetation dynamics in river corridors: A review of complementary approaches. Earth-Science Rev. 84, 56–86. https://doi.org/10.1016/j.earscirev.2007.05.004

Corenblit, D., Steiger, J., Gurnell, A.M., Tabacchi, E., Roques, L. (2009). Control of sediment dynamics by vegetation as a key function driving biogeomorphic succession within fluvial corridors. Earth Surf. Process. Landforms 34, 1790–1810. https://doi.org/10.1002/esp.1876Crochemore, L., Isberg, K., Pimentel, R., Pineda, L., Hasan, A., & Arheimer, B. (2019). Lessons learnt from checking the quality of openly accessible river flow data worldwide. Hydrological Sciences Journal, https://doi.org/10.1080/02626667.2019.1659509

Crutzen, P.J. (2002). Geology of mankind. *Nature* 415, 23. DOI: 10.1038/415023a

Cunningham, S.C., Griffioen, P., White, M.D., & Nally, R.M. (2018). Assessment of ecosystems: A system for rigorous and rapid mapping of floodplain forest condition for Australia's most important river. *Land Degradation & Development 29*, 127–137.

Czuba, J. A. (2018). A Lagrangian framework for exploring complexities of mixed-size sediment transport in gravel-bedded river networks. *Geomorphology*, *321*, 146-152. DOI: 10.1016/j.geomorph.2018.08.031

Czuba, J. A., & Foufoula-Georgiou, E. (2014). A network-based framework for identifying potential synchronizations and amplifications of sediment delivery in river basins. *Water Resources Research*, *50*(5), 3826-3851. DOI: 10.1002/ 2013WR014227

Darby, S. E., Leyland, J., Kummu, M., Räsänen, T. A., & Lauri, H. (2013). Decoding the drivers of bank erosion on the Mekong river: The roles of the Asian monsoon, tropical storms, and snowmelt. *Water Resources Research*, 49(4), 2146-2163.

Demarchi, L., Bizzi, S., & Piégay, H. (2016). Hierarchical object-based mapping of riverscape units and in-stream mesohabitats using LiDAR and VHR imagery. *Remote Sensing*, *8*(2), 97. DOI: 10.3390/rs8020097

Demarchi, L., Bizzi, S., & Piégay, H. (2017). Regional hydromorphological characterization with continuous and automated remote sensing analysis based on VHR imagery and low-resolution LiDAR data. *Earth Surface Processes and Landforms*, *42*(3), 531-551. DOI: 10.1002/esp.4092

Dépret, T., Riquier, J., & Piégay, H. (2017). Evolution of abandoned channels: Insights on controlling factors in a multi-pressure river system. *Geomorphology*, *294*, 99-118.

Detert, M., & Weitbrecht, V. (2012). Automatic object detection to analyze the geometry of gravel grains–a free stand-alone tool. In: River flow 2012: Proceedings of the international conference on fluvial hydraulics, San José, Costa Rica, 5-7. Taylor & Francis Group London, 595-600.

Dewan, A., Corner, R., Saleem, A., Rahman, M.M., Haider, M.R., Rahman, M.M., Sarker, M.H. (2017). Assessing channel changes of the Ganges-Padma River system in Bangladesh using Landsat and hydrological data . *Geomorphology,* 276, 257–279.

Dick, J., Orenstein, D. E., Holzer, J. M., Wohner, C., Achard, A. L., Andrews, C., ... & Van Ryckegem, G. (2018). What is socio-ecological research delivering? A literature survey across 25 international LTSER platforms. *Science of the Total Environment*, *622*, 1225-1240.

Diepenbroek, M, Bartholomä, A, Ibbeken, H. (1992). How round is round? A new approach to the topic 'roundness' by Fourier grain shape analysis. Sedimentology **39**: 411–422. DOI: 10.1111/j.1365-3091.1992.tb02125.x

Dietrich, J.T. (2016). Riverscape mapping with helicopter-based Structure-from-Motion photogrammetry. *Geomorphology*, *252*, 144-157.

Dietrich, J. T. (2017). Bathymetric structure-from-motion: extracting shallow stream bathymetry from multi-view stereo photogrammetry. *Earth Surface Processes and Landforms*, *42*(2), 355-364.

Dietrich, W. E., Kirchner, J. W., Ikeda, H., & Iseya, F. (1989). Sediment supply and the development of the coarse surface layer in gravel-bedded rivers. *Nature*, *340*(6230), 215-217.

Do, H. X., Gudmundsson, L., Leonard, M., Westra, S., & Grabs, W. (2018). The Global Streamflow Indices and Metadata Archive (GSIM)-Part 1: The production of a daily streamflow archive and metadata. *Earth System Science Data*, *10*(2).

Domokos, G, Jerolmack, DJ, Sipos, AÁ, Török, Á. (2014). How river rocks round: Resolving the shape-size paradox. PLoS ONE **9**: 1–7. DOI: 10.1371/journal.pone.0088657

Donchyts, G, Baart, F., Winsemius, H., Gorelick, N., Kwadijk, J., Van De Giesen N. (2016). Earth's surface water change over the past 30 years, 2016. Nature Climate Change, 6 (9), 810. https://doi.org/10.1038/nclimate3111

Downs, P.W., Soar, P.J., Taylor, A. (2016). The anatomy of effective discharge: the dynamics of coarse sediment transport revealed using continuous bedload monitoring in a gravel-bed river during a very wet year. Earth Surface Processes and Landforms, 41(2), 147-161.

Downs, P.W. & Piégay H. (2019). Catchment-scale cumulative impact of human activities on river channels in the late Anthropocene: implications, analytical limitations and prospect. *Geomorphology 338*, 88–104. https://doi.org/10.1016/j.geomorph.2019.03.021.

Dufour, S., Barsoum, N., Muller, E., & Piégay, H. (2007). Effects of channel confinement on pioneer woody vegetation structure, composition and diversity along the River Drôme (SE France). *Earth Surface Processes and Landforms*, *32*(8), 1244-1256.

Dufour, S., & Piégay, H. (2009). From the myth of a lost paradise to targeted river restoration: forget natural references and focus on human benefits. *River research and applications*, *25*(5), 568-581. DOI: 10.1002/rra.1239.

Dufour, S., Muller, E., Straatsma, M., & Corgne, S. (2012). Image Utilisation for the Study and Management of Riparian Vegetation: Overview and Applications. In: Carbonneau, P.E., & Piégay, H. (Eds), *Fluvial Remote Sensing for Science and Management*, Chichester, UK: John Wiley & Sons, Ltd, Chapter 10, 215–239.

Dufour, S., Rinaldi, M., Piégay, H., & Michalon, A. (2015). How do river dynamics and human influences affect the landscape pattern of fluvial corridors? Lessons from the Magra River, Central–Northern Italy. *Landscape and Urban Planning*, *134*, 107-118.

Dunesme S., Melun G., Mustière S., Piégay H., 2018. Automatic vectorization of historical maps: a way to characterize fluvial corridors evolution at a regional scale? Conference I.S.Rivers 2018, Lyon, France, 3 p.

Džubáková, K., Molnar, P., Schindler, K., & Trizna, M. (2015). Monitoring of riparian vegetation response to flood disturbances using terrestrial photography. *Hydrology and Earth System Sciences*, *19*(1), 195-208. DOI: 10.5194/hess-19-195-2015.

Entwistle, N. S., & Fuller, I. C. (2009). Terrestrial laser scanning to derive the surface grain size facies character of gravel bars. *Laser Scanning for the Environmental Sciences*, 102-114.

Entwistle, N., Heritage, G., & Milan, D. (2018). Recent remote sensing applications for hydro and morphodynamic monitoring and modelling. *Earth Surface Processes and Landforms*, *43*(10), 2283-2291.https://doi.org/10.1002/esp.4378

Farid, A., Rautenkranz, D., Goodrich, D. C., Marsh, S. E., & Sorooshian, S. (2006). Riparian vegetation classification from airborne laser scanning data with an emphasis on cottonwood trees. *Canadian Journal of Remote Sensing*, *32*(1), 15-18.

Feurer D, Bailly J-S, Puech C, Le Coarer Y, Viau AA. (2008). Very-high-resolution mapping of river-immersed topography by remote sensing. Progress in Physical Geography, **32**, 403–419.

Fonstad MA, Marcus WA. (2005). Remote sensing of stream depths with hydraulically assisted bathymetry (HAB) models. Geomorphology, **72**, 320–339.

Fonstad, M. A., Dietrich, J. T., Courville, B. C., Jensen, J. L., & Carbonneau, P. E. (2013). Topographic structure from motion: a new development in photogrammetric measurement. *Earth Surface Processes and Landforms*, *38*(4), 421-430.

Fryirs, K. A., & Brierley, G. J. (2012). *Geomorphic analysis of river systems: an approach to reading the landscape*. John Wiley & Sons.

Fryirs, K. A., Brierley, G. J., & Erskine, W. D. (2012). Use of ergodic reasoning to reconstruct the historical range of variability and evolutionary trajectory of rivers. *Earth Surface Processes and Landforms*, *37*(7), 763-773.DOI: 10.1002/esp.3210

Fryirs, K. (2013). (Dis) Connectivity in catchment sediment cascades: a fresh look at the sediment delivery problem. *Earth Surface Processes and Landforms*, *38*(1), 30-46. DOI: 10.1002/esp.3242

Fryirs, K. A. (2017). River sensitivity: a lost foundation concept in fluvial geomorphology. *Earth Surface Processes and Landforms*, *42*(1), 55-70. DOI: 10.1002/esp.3940

Fryirs, K. A., Wheaton, J., Bizzi, S., Williams, R., & Brierley, G. J., (2019). To plug-in or not to plug-in? Geomorphic analysis of rivers using the River Styles Framework in an era of big data acquisition and automation, WiresWater, https://doi.org/10.1002/wat2.1372 [on-line]

Gasser, E, Schwarz, M, Simon, A, Perona, P, Phillips, C, Hübl, J, Dorren, L. (2019). A review of modeling the effects of vegetation on large wood recruitment processes in mountain catchments. Earth-Science Reviews DOI: 10.1016/j.earscirev.2019.04.013 [online]

Geerling, G. W., Vreeken-Buijs, M. J., Jesse, P., Ragas, A. M. J., & Smits, A. J. M. (2009). Mapping river floodplain ecotopes by segmentation of spectral (CASI) and structural (LiDAR) remote sensing data. *River research and applications*, *25*(7), 795-813.

Gilbert, G. K. (1917). *Hydraulic-mining debris in the Sierra Nevada* (No. 105). US Government Printing Office: Menlo Park, CA.

Gilbert, J. T., Macfarlane, W. W., & Wheaton, J. M. (2016). The Valley Bottom Extraction Tool (V-BET): A GIS tool for delineating valley bottoms across entire drainage networks. *Computers & geosciences*, *97*, 1-14. DOI: 10.1016/j.cageo.2016.07.014

Gilvear, D., Winterbottom, S., & Sichingabula, H. (2000). Character of channel planform change and meander development: Luangwa River, Zambia. *Earth Surface Processes and Landforms*, *25*(4), 421-436.

Gilvear, D., & Bryant, R. (2016). Analysis of remotely sensed data for fluvial geomorphology and river science. In Kondolf, G.M. & Piégay, H. (eds.): *Tools in Fluvial Geomorphology, Second Edition*. Chichester, UK: John Wiley & Sons, 103-132.

Gilvear, D. J., Hunter, P., Stewardson, M., Greenwood, M. T., Thoms, M. C., & Wood, P. J. (2016). Remote sensing: mapping natural and managed river corridors from the micro to the network scale. In Gilvear, D. J., Greenwood, M. T., Thoms, M. C., & Wood, P. J. (eds): *River science: Research and management for the 21st century*, 171-196.

Giuliani, G, Chatenoux, B, De Bono, A, Rodila, D, Richard, J-P, Allenbach, K, Dao, H, Peduzzi, P. (2017). Building an Earth Observations Data Cube: lessons learned from the Swiss Data Cube (SDC) on generating Analysis Ready Data (ARD). Big Earth Data **1**: 100–117. DOI: 10.1080/20964471.2017.1398903

Gob, F., Bilodeau, C., Thommeret, N., Belliard, J., Albert, M. B., Tamisier, V., ... & Kreutzenberger, K. (2014). Un outil de caractérisation hydromorphologique des cours d'eau pour l'application de la DCE en France (CARHYCE). *Géomorphologie: relief, processus, environnement*, *20*(1), 57-72. DOI: 10.4000/geomorphologie.10497

Goetz, S. J. (2006). Remote sensing of riparian buffers: Past progress and future prospects. *JAWRA Journal of the American Water Resources Association*, *42*(1), 133-143.

Golly, A. and Turowski, J. M. (2017). Deriving principal channel metrics from bank and long-profile geometry with the R package cmgo, Earth Surf. Dynam., 5, 557-570, https://doi.org/10.5194/esurf-5-557-2017.

Grabowski, R.C., Surian, N., & Gurnell, A.M. (2014). Characterizing geomorphological change to support sustainable river restoration and management. WIREs Water 2014, 1:483–512. doi: 10.1002/wat2.1037.

Grabowski, R. C., & Gurnell, A. M. (2016). Using historical data in fluvial geomorphology. In: Kondolf, G.M., & Piégay, H., (eds). *Tools in Fluvial Geomorphology*. Chichester, UK: John Wiley & Sons, 56-76.

Graham, D. J., Reid, I., & Rice, S. P. (2005 a). Automated sizing of coarse-grained sediments: image-processing procedures. *Mathematical Geology*, *37*(1), 1-28.

Graham, D. J., Rice, S. P., & Reid, I. (2005 b). A transferable method for the automated grain sizing of river gravels. *Water Resources Research*, *41*(7).

Green, R. H. (1979). *Sampling design and statistical methods for environmental biologists*. John Wiley & Sons.

Gregory, V. & Meleason, M. A. (2003). Modeling the Dynamics of Wood in Streams and Rivers History of Wood Models. In: Gregory, S. V, Boyer, K. L. & Gurnell, A. M. (Eds.). *The Ecology and Management of Wood in World Rivers*.

Grigillo, D., Vrečko, A., Mikoš, M., Gvozdanović, T., Anžur, A., & Petrovič, D. (2015). Determination of large wood accumulation in a steep forested torrent using laser scanning. In *Engineering Geology for Society and Territory-Volume 3* (pp. 127-130). Springer, Cham.

Grosso, C., & Azimi-Gaylon, S. (2018). Delta Environmental Data to Understand a California Estuary (DEDUCE): An Estuary-Wide Data Repository. In *I.S.Rivers International Conference 2018, Lyon, France*.

Grill, G., B. Lehner, M. Thieme, B. Geenen, D. Tickner, F. Antonelli, S. Babu, P. Borrelli, L. Cheng, Crochetiere, H., … & Zarfl, C. (2019). Mapping the world's free-flowing rivers. *Nature* 569, 7755: 215.

Guerit, L., Barrier, L., Narteau, C., Métivier, F., Liu, Y., Lajeunesse, E., ... & Ye, B. (2014). The Grain-size Patchiness of Braided Gravel-Bed Streams–example of the Urumqi River (northeast Tian Shan, China). *Advances in Geosciences*, *37*, 27-39.

Gurnell, A. M., Downward, S. R. Jones, R. (1994). Channel planform change on the river dee meanders, 1876–1992. *Regul. Rivers: Res. Mgmt.*, *9*: 187-204.

Gurnell, A.M., Bertoldi, W., Corenblit, D., (2012). Changing river channels: The roles of hydrological processes, plants and pioneer fluvial landforms in humid temperate, mixed load, gravel bed rivers. Earth-Science Rev. 111, 129–141. https://doi.org/10.1016/j.earscirev.2011.11.005

Gurnell, A. M., Rinaldi, M., Belletti, B., Bizzi, S., Blamauer, B., Braca, G., ... & Demarchi, L. (2016). A multi-scale hierarchical framework for developing understanding of river behaviour to support river management. *Aquatic Sciences*, *78*(1), 1-16. https://doi.org/10.1007/s00027-015-0424-5.

Haase, P., Frenzel, M., Klotz, S., Musche, M., & Stoll, S. (2016). The long-term ecological research (LTER) network: Relevance, current status, future perspective and examples from marine, freshwater and terrestrial long-term observation. *Ecological Indicators*, (65), 1-3.

Hammersmark, C. T., Dobrowski, S. Z., Rains, M. C., & Mount, J. F. (2010). Simulated effects of stream restoration on the distribution of wet-meadow vegetation. *Restoration Ecology*, *18*(6), 882-893.

Hayakawa, Y, Oguchi, T. (2005). Evaluation of gravel sphericity and roundness based on surface-area measurement with a laser scanner. Computers and Geosciences **31**: 735–741. DOI: 10.1016/j.cageo.2005.01.004

Heckmann, T., & Schwanghart, W. (2013). Geomorphic coupling and sediment connectivity in an alpine catchment—Exploring sediment cascades using graph theory. *Geomorphology*, *182*, 89-103. DOI: 10.1016/j.geomorph.2012.10.033.

Heckmann, T., Schwanghart, W., & Phillips, J. D. (2015). Graph theory—Recent developments of its application in geomorphology. *Geomorphology*, *243*, 130-146. DOI: 10.1016/j.geomorph.2014.12.024.

Heckmann, T., Haas, F., Abel, J., Rimböck, A., & Becht, M. (2017). Feeding the hungry river: Fluvial morphodynamics and the entrainment of artificially inserted sediment at the dammed river Isar, Eastern Alps, Germany. *Geomorphology*, *291*, 128-142. DOI: https://doi.org/10.1016/j.geomorph.2017.01.025

Heckmann, T., Cavalli, M., Cerdan, O., Foerster, S., Javaux, M., Lode, E., ... & Brardinoni, F. (2018). Indices of sediment connectivity: opportunities, challenges and limitations. *Earth-science reviews*, *187*, 77–108. DOI: 10.1016/j.earscirev.2018.08.004

Henshaw, A. J., Gurnell, A. M., Bertoldi, W., & Drake, N. A. (2013). An assessment of the degree to which Landsat TM data can support the assessment of fluvial dynamics, as revealed by changes in vegetation extent and channel position, along a large river. *Geomorphology*, *202*, 74-85.

Hervouet, A., Dunford, R., Piégay, H., Belletti, B., & Trémélo, M. L. (2011). Analysis of post-flood recruitment patterns in braided-channel rivers at multiple scales based on an image series collected by unmanned aerial vehicles, ultra-light aerial vehicles, and satellites. *GIScience & Remote Sensing*, *48*(1), 50-73.

Heritage, G. L., & Milan, D. J. (2009). Terrestrial laser scanning of grain roughness in a gravel-bed river. *Geomorphology*, *113*(1-2), 4-11.

Hersbach, H., de Rosnay, P., Bell, B., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Alonso-Balmaseda, M., Balsamo, G., Bechtold, P., Berrisford, P., Bidlot, J.-R., de Boisséson, E., Bonavita, M., Browne, P., Buizza, R., Dahlgren, P., Dee, D., Dragani, R., Diamantakis, M., Flemming, J., Forbes, R., Geer, A. J., Haiden, T., Hólm, E., Haimberger, L., Hogan, R., Horányi, A., Janiskova, M., Laloyaux, P., Lopez, P., Munoz-Sabater, J., Peubey, C., Radu, R., Richardson, D., Thépaut, J.-N., Vitart, F., Yang, X., Zsótér, E., and Zuo, H.: (2018). Operational global reanalysis: progress, future directions and synergies with NWP. European Centre for Medium Range Weather Forecasts.

Hicks, D. M., Shankar, U., Duncan, M. J., Rebuffé, M., & Aberle, J. (2009). Use of remote-sensing with two-dimensional hydrodynamic models to assess impacts of hydro-operations on a large, braided, gravel-bed river: Waitaki River, New Zealand. In: Sambrook Smith, G.H., Best, J.L., Bristow, C.S., Petts, G.E. & Jarvis, I. (eds) *Braided Rivers: Process, Deposits, Ecology and Management*, John Wiley and Sons: Chichester, 311-326.

Hirpa, F. A., Hopson, T. M., De Groeve, T., Brakenridge, G. R., Gebremichael, M., & Restrepo, P. J. (2013). Upstream satellite remote sensing for river discharge forecasting: Application to major rivers in South Asia. *Remote Sensing of Environment*, *131*, 140-151.

Hobbs, R. J., Arico, S., Aronson, J., Baron, J. S., Bridgewater, P., Cramer, V. A., ... & Norton, D. (2006). Novel ecosystems: theoretical and management aspects of the new ecological world order. *Global ecology and biogeography*, *15*(1), 1-7.

Hodge, R., Brasington, J., & Richards, K. (2009). In situ characterization of grain-scale fluvial morphology using Terrestrial Laser Scanning. *Earth Surface Processes and Landforms*, *34*(7), 954-968.

Hooke, J. (2003). River meander behaviour and instability: a framework for analysis. *Transactions of the Institute of British Geographers*, 28(2), 238-253.

Horacio, J., Dunesme, S., Piégay, H. (on line) Comparison of historical topographic maps across four countries to characterise river corridor evolution at a continental scale. River Research and Applications

Hortobágyi, B., Corenblit, D., Vautier, F., Steiger, J., Roussel, E., Burkart, A., & Peiry, J. L. (2017). A multi-scale approach of fluvial biogeomorphic dynamics using photogrammetry. *Journal of environmental management*, *202*, 348-362.

Huang, W. C., Young, C. C., & Liu, W. C. (2018). Application of an automated discharge imaging system and LSPIV during typhoon events in Taiwan. *Water*, *10*(3), 280. https://doi.org/10.3390/w10030280.

Husson, E., Ecke, F., & Reese, H. (2016). Comparison of manual mapping and automated object-based image analysis of non-submerged aquatic vegetation from very-high-resolution UAS images. *Remote Sensing*, *8*(9), 724.

Ibbeken, H., & Schleyer, R. (1986). Photo-sieving: A method for grain-size analysis of coarse-grained, unconsolidated bedding surfaces. *Earth Surface Processes and Landforms*, *11*(1), 59-77.Isikdogan, F., Bovik, A., & Passalacqua, P. (2017). RivaMap: An automated river analysis and mapping engine. *Remote Sensing of Environment*, *202*, 88-97. https://doi.org/10.1016/j.rse.2017.03.044.

Jain, V., Preston, N., Fryirs, K., & Brierley, G. (2006). Comparative assessment of three approaches for deriving stream power plots along long profiles in the upper Hunter River catchment, New South Wales, Australia. *Geomorphology*, *74*(1-4), 297-317.

James, L. A. (1991). Incision and morphologic evolution of an alluvial channel recovering from hydraulic mining sediment. *Geological Society of America Bulletin*, *103*(6), 723-736. DOI: 10.1130/0016-7606(1991)103<0723.

James, A. (1999). Time and the persistence of alluvium: River engineering, fluvial geomorphology, and mining sediment in California. *Geomorphology*, *31*(1-4), 265-290. DOI: 10.1016/S0169-555X(99)00084-7.

James, M. R., & Robson, S. (2012). Straightforward reconstruction of 3D surfaces and topography with a camera: Accuracy and geoscience application. *Journal of Geophysical Research: Earth Surface*, *117*(F3).

James LA, Hodgson ME, Ghoshal S, Latiolais MM. (2012). Geomorphic change detection using historic maps and DEM differencing: The temporal dimension of geospatial analysis. Geomorphology, **137**, 181–198.

James MR, Robson S. (2014). Mitigating systematic error in topographic models derived from UAV and ground-based image networks. Earth Surface Processes and Landforms, **39**, 1413–1420.

James, M. R., Robson, S., d'Oleire-Oltmanns, S., & Niethammer, U. (2017). Optimising UAV topographic surveys processed with structure-from-motion: Ground control quality, quantity and bundle adjustment. *Geomorphology*, *280*, 51-66.

Jodeau, M., Hauet, A., & Bercovitz, Y. (2017). Laboratory and field LSPIV measurements of flow velocities using Fudaa-LSPIV a free user-friendly software, In: HydroSenSoft, *Proc. 1st International Symposium and Exhibition on Hydro-Environment Sensors and Software*. 82-86.

Johansen, K., Phinn, S., & Witte, C. (2010). Mapping of riparian zone attributes using discrete return LiDAR, QuickBird and SPOT-5 imagery: Assessing accuracy and costs. *Remote Sensing of Environment*, *114*(11), 2679-2691.

Johansen, K., Coops, N. C., Gergel, S. E., & Stange, Y. (2007). Application of high spatial resolution satellite imagery for riparian and forest ecosystem classification. *Remote sensing of Environment*, *110*(1), 29-44.

Jugie, M., Gob, F., Virmoux, C., Brunstein, D., Tamisier, V., Le Coeur, C., & Grancher, D. (2018). Characterizing and quantifying the discontinuous bank erosion of a small low energy river using Structure-from-Motion Photogrammetry and erosion pins. *Journal of hydrology*, *563*, 418-434.

Kaneko, K., & Nohara, S. (2014). Review of effective vegetation mapping using the UAV (Unmanned Aerial Vehicle) method. *Journal of Geographic Information System*, *6*(06), 733.

Kasprak, A., Magilligan, F. J., Nislow, K. H., & Snyder, N. P. (2012). A LiDAR -derived evaluation of watershed-scale large woody debris sources and recruitment mechanisms: Coastal Maine, USA. *River Research and Applications*, *28*(9), 1462-1476.

Kondolf, G. M., Piégay, H., & Landon, N. (2007). Changes in the riparian zone of the lower Eygues River, France, since 1830. *Landscape Ecology*, *22*(3), 367-384.

Kinzel PJ, Wright CW, Nelson JM, Burman AR. (2007). Evaluation of an experimental LiDAR for surveying a shallow, braided, sand-bedded river. Journal of Hydraulic Engineering, **133**, 838–842.

Kramer, N., & Wohl, E. (2014). Estimating fluvial wood discharge using time‐lapse photography with varying sampling intervals. *Earth Surface Processes and Landforms*, *39*(6), 844-852. https://doi.org/10.1002/esp.3540

Kramer, N., Bangen, S. G., Wheaton, J. M., Bouwes, N., Wall, E., Saunders, C., ... & Fortney, S. (2017). Geomorphic Unit Tool (GUT): Applications of Fluvial Mapping. In *AGU Fall Meeting Abstracts*. EP11A-1546. AGU, New Orleans, LA, 11-15 Dec. DOI: 10.13140/RG.2.2.30142.18241

Kui, L., Stella, J. C., Shafroth, P. B., House, P. K., & Wilcox, A. C. (2017). The long‐term legacy of geomorphic and riparian vegetation feedbacks on the dammed Bill Williams River, Arizona, USA. *Ecohydrology*, *10*(4). https://doi.org/10.1002/eco.1839

Lallias-Tacon, S., Liébault, F., & Piégay, H. (2014). Step by step error assessment in braided river sediment budget using airborne LiDAR data. *Geomorphology*, *214*, 307-323

Lallias-Tacon, S., Liébault, F., & Piégay, H. (2017). Use of airborne LiDAR and historical aerial photos for characterising the history of braided river floodplain morphology and vegetation responses. *Catena*, *149*, 742-759.

Lane, S.N., Richards, K.S., & Chandler, J.H. (1994). Developments in monitoring and modelling small-scale river bed topography. Earth Surface Processes and Landforms, **19**, 349–368.

Lane, S.N., Richards, K.S., & Chandler, J.H. (1995). Morphological estimation of the time-integrated bed load transport rate. Water Resources Research, **31**, 761–772.

Lane, S. N. (2000). The measurement of river channel morphology using digital photogrammetry. *The Photogrammetric Record*, *16*(96), 937-961.

Lane, S. N., Westaway, R. M., & Murray Hicks, D. (2003). Estimation of erosion and deposition volumes in a large, gravel‐bed, braided river using synoptic remote sensing. *Earth Surface Processes and Landforms*, *28*(3), 249-271.

Lane SN, Widdison PE, Thomas RE, Ashworth PJ, Best JL, Lunt IA, Sambrook Smith GH, Simpson CJ. (2010). Quantification of braided river channel change using archival digital image analysis. Earth Surface Processes and Landforms, **35**, 971–985.

Langhammer, J., & Vacková, T. (2018). Detection and mapping of the geomorphic effects of flooding using UAV photogrammetry. *Pure and Applied Geophysics*, *175*, 3223-3245. doi:10.1007/s00024-018-1874-1

Laslier, M., Hubert-Moy, L., & Dufour, S. (2019a). Mapping Riparian Vegetation Functions Using 3D Bispectral LiDAR Data. *Water*, *11*(3), 483.

Laslier, M., Corpetti, T., Hubert-Moy, L., & Dufour, S. (*2019b*). Monitoring the colonization of alluvial deposits using multitemporal UAV RGB-imagery. A*pplied Vegetation Science, DOI: 10.1111/avsc.12455*

Lassettre, N. S., Piégay, H., Dufour, S., & Rollet, A. J. (2008). Decadal changes in distribution and frequency of wood in a free meandering river, the Ain River, France. *Earth Surface Processes and Landforms*, *33*(7), 1098-1112.

Lauer, W. J. (2006). Planform Statistics, NCED Stream Restoration Toolbox. National Center for Earth-Surface Dynamics, University of Minnesota, Minneapolis, MN, St. Anthony Falls Lab.

Le Boursicaud, R., Pénard, L., Hauet, A., Thollet, F., & Le Coz, J. (2016). Gauging extreme floods on YouTube: application of LSPIV to home movies for the post-event determination of stream discharges. *Hydrological Processes*, *30*(1), 90-105. https://doi.org/10.1002/hyp.10532

Le Coz, J., Hauet, A., Pierrefeu, G., Dramais, G., & Camenen, B. (2010). Performance of image-based velocimetry (LSPIV) applied to flash-flood discharge measurements in Mediterranean rivers. *Journal of hydrology*, *394*(1-2), 42-52. doi:10.1016/j.jhydrol.2010.05.049

Le Coz, J., Patalano, A., Collins, D., Guillén, N. F., García, C. M., Smart, G. M., ... & Braud, I. (2016). Crowdsourced data for flood hydrology: Feedback from recent citizen science projects in Argentina, France and New Zealand. *Journal of Hydrology*, *541*, 766-777. doi:10.1016/j.jhydrol.2016.07.036

Lehmann, A, Giuliani, G, Ray, N, Rahman, K, Abbaspour, KC, Nativi, S, Craglia, M, Cripe, D, Quevauviller, P, Beniston, M. (2014). Reviewing innovative Earth observation solutions for filling science-policy gaps in hydrology. Journal of DOI: 10.1016/j.jhydrol.2014.05.059

Lehmann, A, Chaplin-Kramer, R, Lacayo, M, Giuliani, G, Thau, D, Koy, K, Goldberg, G, Sharp, R. (2017). Lifting the information barriers to address sustainability challenges with data from physical geography and Earth observation. Sustainability (Switzerland) **9**: 1–15. DOI: 10.3390/su9050858

Legleiter, C. J. (2012). Remote measurement of river morphology via fusion of LiDAR topography and spectrally based bathymetry. *Earth Surface Processes and Landforms*, *37*(5), 499-518.

Legleiter CJ, Overstreet BT, Glennie CL, Pan Z, Fernandez-Diaz JC, & Singhania A. (2016). Evaluating the capabilities of the CASI hyperspectral imaging system and Aquarius bathymetric LiDAR for measuring channel morphology in two distinct river environments. Earth Surface Processes and Landforms, **41**, 344–363.

Lehner, B., Verdin, K., and Jarvis, A. 2008. New global hydrograhy derived from spaceborne elevation data. Eos, Trans. Am. Geophys. Union 89(10), 93–94.

Lehner, B., Liermann, C. R., Revenga, C., Vörösmarty, C., Fekete, B., Crouzet, P., ... & Nilsson, C. (2011). Global reservoir and dam (grand) database. *Technical Documentation, Version*, *1*.

Liébault, F., Piégay, H. (2002). Causes of 20th century channel narrowing in mountain and piedmont rivers of Southeastern France. *Earth Surface Processes and Landforms*, **27**, 425-444

Liébault, F., Clément, P., Piégay, H., Rogers, C. F., Kondolf, G. M., & Landon, N. (2002). Contemporary channel changes in the Eygues basin, southern French Prealps: the relationship of subbasin variability to watershed characteristics. *Geomorphology*, *45*(1-2), 53-66.

Liébault, F., Bellot, H., Chapuis, M., Klotz, S., & Deschâtres, M. (2012). Bedload tracing in a high-sediment-load mountain stream. *Earth Surface Processes and Landforms*, *37*(4), 385-399. DOI: 10.1002/esp.2245

Liébault, F., Lallias-Tacon, S., Cassel, M., & Talaska, N. (2013). Long profile responses of alpine braided rivers in SE France. *River Research and Applications*, *29*(10), 1253-1266.

Lindsey, D.A., Langer, W.H., Van Gosen, B.S. (2007). Using pebble lithology and roundness to interpret gravel provenance in piedmont fluvial systems of the Rocky Mountains, USA. Sedimentary Geology **199**: 223–232. DOI: 10.1016/j.sedgeo.2007.02.006

Litty, C, Schlunegger, F. (2016). Controls on Pebbles' Size and Shape in Streams of the Swiss Alps. The Journal of Geology **125**: 101–112. DOI: 10.1086/689183

Loicq, P., Moatar, F., Jullian, Y., Dugdale, S. J., & Hannah, D. M. (2018). Improving representation of riparian vegetation shading in a regional stream temperature model using LiDAR data. *Science of the Total Environment*, *624*, 480-490.

Macfarlane, W. W., Gilbert, J. T., Jensen, M. L., Gilbert, J. D., Hough-Snee, N., McHugh, P. A., ... & Bennett, S. N. (2017). Riparian vegetation as an indicator of riparian condition: Detecting departures from historic condition across the North American West. *Journal of environmental management*, *202*, 447-460. https://doi.org/10.1016/j.jenvman.2016.10.054

MacVicar, B. J., Piégay, H., Henderson, A., Comiti, F., Oberlin, C., & Pecorari, E. (2009). Quantifying the temporal dynamics of wood in large rivers: field trials of wood surveying, dating, tracking, and monitoring techniques. *Earth Surface Processes and Landforms*, *34*(15), 2031-2046.

MacVicar, B.J., Hauet, A., Bergeron, N., Tougne, L., Ali, I. (2012). River Monitoring with Ground-based Videography. In: Carbonneau, P.E., & Piégay, H. (Eds), *Fluvial Remote Sensing for Science and Management*, Chichester, UK: John Wiley & Sons, Ltd

MacVicar, B., & Piégay, H. (2012). Implementation and validation of video monitoring for wood budgeting in a wandering piedmont river, the Ain River (France). *Earth Surface Processes and Landforms*, *37*(12), 1272-1289.

Mandlburger, G., Hauer, C., Wieser, M., & Pfeifer, N. (2015). Topo-bathymetric LiDAR for monitoring river morphodynamics and instream habitats—A case study at the Pielach River. *Remote Sensing*, *7*(5), 6160-6195.

Marchese, E., Scorpio, V., Fuller, I., McColl, S., & Comiti, F. (2017). Morphological changes in Alpine rivers following the end of the Little Ice Age. *Geomorphology*, *295*, 811-826.

Marcus WA. (2002). Mapping of stream microhabitats with high spatial resolution hyperspectral imagery. Journal of geographical systems **4**, 113–126.

Marcus, W. A., Marston, R. A., Colvard Jr, C. R., & Gray, R. D. (2002). Mapping the spatial and temporal distributions of woody debris in streams of the Greater Yellowstone Ecosystem, USA. *Geomorphology*, *44*(3-4), 323-335.

Marcus, W. A., Legleiter, C. J., Aspinall, R. J., Boardman, J. W., & Crabtree, R. L. (2003). High spatial resolution hyperspectral mapping of in-stream habitats, depths, and woody debris in mountain streams. *Geomorphology*, *55*(1-4), 363-380.

Marcus, W. A., & Fonstad, M. A. (2010). Remote sensing of rivers: the emergence of a subdiscipline in the river sciences. *Earth Surface Processes and Landforms*, *35*(15), 1867-1872.

Martínez--Fernández, V., González del Tánago, M., Maroto, J., & García de Jalón, D. (2017). Fluvial corridor changes over time in regulated and non-regulated rivers (Upper Esla River, NW Spain). *River research and applications*, *33*(2), 214-223.

Martinez, A.E., Adeyemo, A.E., & Walther, S.C. (2018). Riparian vegetation and digitized channel variable changes after stream impoundment: the Provo River and Jordanelle Dam, *Int. J. Appl. Geospatial Res*. 9, 19–35.

Mazzorana, B., Zischg, A., Largiader, A., & Hübl, J. (2009). Hazard index maps for woody material recruitment and transport in alpine catchments. *Natural Hazards and Earth System Sciences*, *9*(1), 197-209.

McKean, J., Nagel, D., Tonina, D., Bailey, P., Wright, C.W., Bohn, C., & Nayegandhi, A., 2009. Remote sensing of channels and riparian zones with a narrow-beam aquatic-terrestrial lidar. Remote Sensing, 1, 1065-1096. doi:10.3390/rs1041065.

Meybeck, M., & Lestel, L. (2017). A Western European River in the Anthropocene: The Seine, 1870–2010. In: Kelly, J. et al. (eds), *Rivers of the Anthropocene*. California: University of California Press. DOI: https://doi.org/10.1525/luminos.43.g

Michalková, M., Piégay, H., Kondolf, G. M., & Greco, S. E. (2011). Lateral erosion of the Sacramento River, California (1942–1999), and responses of channel and floodplain lake to human influences. *Earth Surface Processes and Landforms*, *36*(2), 257-272.

Michez, A., Piégay, H., Lisein, J., Claessens, H., & Lejeune, P. (2016). Classification of riparian forest species and health condition using multi-temporal and hyperspatial imagery from unmanned aerial system. *Environmental monitoring and assessment*, *188*(3), 146.

Michez, A., Piégay, H., Lejeune, P., & Claessens, H. (2017). Multi-temporal monitoring of a regional riparian buffer network (> 12,000 km) with LiDAR and photogrammetric point clouds. *Journal of environmental management*, *202*, 424-436.

Milan, D. J., Heritage, G. L., & Hetherington, D. (2007). Application of a 3D laser scanner in the assessment of erosion and deposition volumes and channel change in a proglacial river. *Earth Surface Processes and Landforms*, *32*(11), 1657-1674.

Milan, D. J., Heritage, G. L., Large, A. R. G., & Entwistle, N. S. (2010). Mapping hydraulic biotopes using terrestrial laser scan data of water surface properties. *Earth Surface Processes and Landforms*, *35*(8), 918-931.

Milan, D. J., Heritage, G. L., Large, A. R., & Fuller, I. C. (2011). Filtering spatial error from DEMs: Implications for morphological change estimation. *Geomorphology*, *125*(1), 160-171.

Milan, D., Heritage, G., Tooth, S., Entwistle, N. (2018). Morphodynamics of bedrock-influenced dryland rivers during extreme floods: Insights from the Kruger National Park, South Africa. GSA Bulletin, 130(11-12), 1825-1841.

Misset, C., Recking, A., Legout, C., Poirel, A., Cazihlac, M., Esteves, M., & Bertrand, M. (2019). An attempt to Link suspended load hysteresis patterns and sediment sources configuration in alpine catchments. *Journal of Hydrology*, https://doi.org/10.1016/j.jhydrol.2019.06.039. (http://www.sciencedirect.com/science/article/pii/S0022169419305864)

Moore, J. W. (2015). *Capitalism in the Web of Life: Ecology and the Accumulation of Capital*. Verso Books. ISBN 9781781689035

Mould, S., & Fryirs, K. (2018). Contextualising the trajectory of geomorphic river recovery with environmental history to support river management. *Applied Geography*, *94*, 130-146. https://doi.org/10.1016/j.apgeog.2018.03.008

Mudd, S. M., F. J. Clubb, B. Gailleton, M. D. Hurst, D. T. Milodowski, & Valters, D. A. (2018). "The LSDTopo-Tools Chi Mapping Package (Version 1.11), Zenodo.".

Muste, M., Ho, H. C., & Kim, D. (2011). Considerations on direct stream flow measurements using video imagery: Outlook and research needs. *Journal of Hydro-environment Research*, *5*(4), 289-300. doi:10.1016/j.jher.2010.11.002

Norman, L., Villarreal, M., Pulliam, H. R., Minckley, R., Gass, L., Tolle, C., & Coe, M. (2014). Remote sensing analysis of riparian vegetation response to desert marsh restoration in the Mexican Highlands. *Ecological Engineering*, *70*, 241-254.

Notebaert, B., & Piégay, H. (2013). Multi-scale factors controlling the pattern of floodplain width at a network scale: The case of the Rhône basin, France. *Geomorphology*, *200*, 155-171.

Nunes, S. S., Barlow, J., Gardner, T. A., Siqueira, J. V., Sales, M. R., & Souza, C. M. (2015). A 22 year assessment of deforestation and restoration in riparian forests in the eastern Brazilian Amazon. *Environmental conservation*, *42*(3), 193-203.

Ollero, A. (2010). Channel changes and floodplain management in the meandering middle Ebro River, Spain. *Geomorphology*, *117*(3-4), 247-260.

Ouellet Dallaire, C., Lehner, B., Sayre, R., & Thieme, M. (2019). A multidisciplinary framework to derive global river reach classifications at high spatial resolution. Environmental Research Letters. DOI: 10.1088/1748-9326/aad8e9

Parker, C., Thorne, C. R., & Clifford, N. J. (2015). Development of ST: REAM: a reach-based stream power balance approach for predicting alluvial river channel adjustment. *Earth Surface Processes and Landforms*, *40*(3), 403-413. DOI: 10.1002/esp.3641

Passalacqua, P., Belmont, P., Staley, D. M., Simley, J. D., Arrowsmith, J. R., Bode, C. A., ... & Wheaton, J. M. (2015). Analyzing high resolution topography for advancing the understanding of mass and energy transfer through landscapes: A review. *Earth-Science Reviews*, *148*, 174-193. DOI: 10.1016/j.earscirev.2015.05.012

Pearson, E., Smith, M.W., Klaar, M.J., & Brown, L.E. (2017). Can high resolution 3D topographic surveys provide reliable grain size estimates in gravel bed rivers? *Geomorphology*, 293, 143–155.

Peerbhay, K., Mutanga, O., Lottering, R., & Ismail, R. (2016). Unsupervised anomaly weed detection in riparian forest areas using hyperspectral data and LiDAR, in: *Hyperspectral Image and Signal Processing: Evolution in Remote Sensing* (WHISPERS), 2016 8th Workshop On. IEEE, pp. 1–5.

Pekel, J. F., Cottam, A., Gorelick, N., & Belward, A. S. (2016). High-resolution mapping of global surface water and its long-term changes. *Nature*, *540*(7633), 418-436. https://doi.org/10.1038/nature20584.

Perks, M. T., Russell, A. J., & Large, A. R. G. (2016). Technical Note: Advances in flash flood monitoring using UAVs. *Hydrology and Earth System Sciences Discussions*. 1–18. doi:10.5194/hess-2016-12

Perucca, E., Camporeale, C., & Ridolfi, L. (2007). Significance of the riparian vegetation dynamics on meandering river morphodynamics. *Water Resources Research*, *43*(3), W03430.

Petts, G.E., Moller, H., Roux, A.L. (1989). Historical change of large alluvial rivers: Western Europe. *John Wiley & Sons, Chichester, 355* p.

Peucker-Ehrenbrink, B. (2009). Land2Sea database of river drainage basin sizes, annual water discharges, and suspended sediment fluxes. *Geochemistry, Geophysics, Geosystems*, *10*(6).

Pickett, S.T.A. (1989). Space-for-Time Substitution as an Alternative to Long-Term Studies. In: Likens G.E. (eds) *Long-Term Studies in Ecology*. Springer, New York, 110-135.

Piégay, H., & Schumm, S. A. (2003). System approaches in fluvial geomorphology. In Kondolf, G.M.& Piégay, H. (eds.): *Tools in Fluvial Geomorphology*. Chichester, UK: John Wiley & Sons, 103-134.

Piégay, H., Grant, G., Nakamura, F., & Trustrum, N. (2006). Braided river management: from assessment of river behaviour to improved sustainable development. *Braided rivers: process, deposits, ecology and management*, *36*, 257-275.

Piégay, H., Kondolf, G. M., Minear, J. T., & Vaudor, L. (2015). Trends in publications in fluvial geomorphology over two decades: A truly new era in the discipline owing to recent technological revolution?. *Geomorphology*, *248*, 489-500.

Piégay, H., Ghaffarian, H., Lemaire, P., Zhang, Z., Boivin, M., Senter, A., ... & Michel, K. (2019). Video-monitoring of wood flux: recent advances and next steps. In *4th international conference in Wood in World Rivers Conference Proceedings*, Valdivia, Chile

Pinter, N., & Heine, R. A. (2005). Hydrodynamic and morphodynamic response to river engineering documented by fixed-discharge analysis, Lower Missouri River, USA. *Journal of Hydrology*, *302*(1-4), 70-91. DOI:10.1016/j.jhydrol.2004.06.039.

Pfeiffer, A. M., & Finnegan, N. J. (2018). Regional Variation in Gravel Riverbed Mobility, Controlled by Hydrologic Regime and Sediment Supply. *Geophysical Research Letters*, 45(7), 3097-3106.

Phillips, C. B., & Jerolmack, D. J. (2016). Self-organization of river channels as a critical filter on climate signals. *Science*, 352(6286), 694-697.Purinton, B., & Bookhagen, B. (2019). Introducing Pebble Counts: A grain-sizing tool for photo surveys of dynamic gravel-bed rivers. Earth Surf. Dyn. Discuss. 1–33. https://doi.org/10.5194/esurf-2019-20

Räpple, B., Piégay, H., Stella, J. C., & Mercier, D. (2017). What drives riparian vegetation encroachment in braided river channels at patch to reach scales? Insights from annual airborne surveys (Drôme River, SE France, 2005–2011). *Ecohydrology*, *10*(8), e1886.

Ravazzolo, D., Mao, L., Mazzorana, B., & Ruiz-Villanueva, V. (2017). Brief communication: The curious case of the large wood-laden flow event in the Pocuro stream (Chile). *Natural Hazards and Earth System Sciences*, *17*(11), 2053-2058. doi:10.5194/nhess-2017-154

Ricaurte, L.F., Boesch, S., Jokela, J., Tockner, K. (2012). The distribution and environmental state of vegetated islands within human-impacted European rivers. *Freshw. Biol. 57*, 2539–2549.

Rice, S., & Church, M. (1998). Grain size along two gravel-bed rivers: statistical variation, spatial pattern and sedimentary links. *Earth Surface Processes and Landforms*, *23*(4), 345-363.

Ridolfi, E., & Manciola, P. (2018). Water level measurements from drones: A pilot case study at a dam site. *Water*, *10*(3), 297. doi:10.3390/w10030297

Riedler, B., Pernkopf, L., Strasser, T., Lang, S., & Smith, G. (2015). A composite indicator for assessing habitat quality of riparian forests derived from Earth observation data. *International Journal of Applied Earth Observation and Geoinformation*, *37*, 114-123.

Rodríguez-González, P. M., Albuquerque, A., Martínez-Almarza, M., & Díaz-Delgado, R. (2017). Long-term monitoring for conservation management: Lessons from a case study integrating remote sensing and field approaches in floodplain forests. *Journal of environmental management*, *202*, 392-402.

Rollet, A.J., Piégay, H., Bornette, G., Dufour, S., & Persat, H. (2013). Assessment of consequences of sediment deficit on a gravel river-bed downstream of dams in restoration perspectives: application of a multicriteria, hierarchical, and spatially explicit diagnosis. *River Research and Applications*, *30*(8), 939-953.

Roussillon, T., Piégay, H., Sivignon, I., Tougne, L., & Lavigne, F. (2009). Automatic computation of pebble roundness using digital imagery and discrete geometry. *Computers & Geosciences*, *35*(10), 1992-2000.

Roux, C., Alber, A., Bertrand, M., Vaudor, L., & Piégay, H. (2015). “Fluvial Corridor”: A new ArcGIS toolbox package for multiscale riverscape exploration. *Geomorphology*, *242*, 29-37. DOI: 10.1016/j.geomorph.2014.04.018

Rubin, D. M. (2004). A simple autocorrelation algorithm for determining grain size from digital images of sediment. *Journal of Sedimentary Research*, *74*(1), 160-165. DOI: 10.1306/052203740160

Ruiz-Villanueva, V., Díez-Herrero, A., Ballesteros, J. A., & Bodoque, J. M. (2014 a). Potential large woody debris recruitment due to landslides, bank erosion and floods in mountain basins: a quantitative estimation approach. *River Research and Applications*, *30*(1), 81-97.

Ruiz-Villanueva, V., Bladé, E., Sánchez-Juny, M., Marti-Cardona, B., Díez-Herrero, A., & Bodoque, J. M. (2014 b). Two-dimensional numerical modeling of wood transport. *Journal of Hydroinformatics*, *16*(5), 1077-1096.

Ruiz-Villanueva, V., Piégay, H., Gurnell, A. M., Marston, R. A., & Stoffel, M. (2016). Recent advances quantifying the large wood dynamics in river basins: New methods and remaining challenges. *Reviews of Geophysics*, *54*(3), 611-652.

Ruiz-Villanueva, V., Mazzorana, B., Bladé, E., Bürkli, L., Iribarren-Anacona, P., Mao, L., Nakamura, F., Ravazzolo , D., Rickenmann, D., Sanz-Ramos, M., Stoffel, M., & Wohl, E. (2019). Characterization of wood-laden flows in rivers. *Earth Surface Processes and Landforms*, 44, 1694–1709. https://doi-org.acces.bibliotheque-diderot.fr/10.1002/esp.4603

Safran, S.M., Baumgarten, S.A., Beller, E.E., Crooks, J.A., Grossinger, R.M., Lorda, J., & Stein, E.D. (2017). Tijuana River Valley Historical Ecology Investigation. Prepared for the State Coastal Conservancy. A Report of SFEI-ASC's Resilient Landscapes Program. SFEI Contribution No. 760. San Francisco Estuary Institute - Aquatic Science Center: Richmond, CA. p 230.

Salo, J., Kalliola, R., Häkkinen, I., Mäkinen, Y., Niemelä, P., Puhakka, M., & Coley, P. D. (1986). River dynamics and the diversity of Amazon lowland forest. *Nature*, *322*(6076), 254-258.

Sanhueza, D., Iroumé, A., Ulloa, H., Picco, L., & Ruiz-Villanueva, V. (2018). Measurement and quantification of fluvial wood deposits using UAVs and structure from motion in the Blanco River (Chile). 5th IAHR Europe Congress — New Challenges in Hydraulic Research and Engineering, Proc. of the 5th IAHR Europe Congress. Editor(s) Armanini, A. & Nucci, E. , DOI:10.3850/978-981-11-2731-1_216-cd.

Santos, P.P., Tavares, A.O., & Andrade, A.I.A.S.S. (2011). Comparing historical-hydrogeomorphological reconstitution and hydrological-hydraulic modelling in the estimation of flood-prone areas-a case study in Central Portugal. *Natural Hazards and Earth System Sciences*, *11*(6), 1669-1681.

Schmitt, R.J., Bizzi, S., & Castelletti, A. (2014). Characterizing fluvial systems at basin scale by fuzzy signatures of hydromorphological drivers in data scarce environments». *Geomorphology* 214 (2014), 69–83. https://doi.org/10.1016/j.geomorph.2014.02.024.

Schmitt, R. J., Bizzi, S., & Castelletti, A. (2016). Tracking multiple sediment cascades at the river network scale identifies controls and emerging patterns of sediment connectivity. *Water Resources Research*, *52*(5), 3941-3965. DOI: 10.1002/2015WR018097

Schmitt, R. J., Bizzi, S., Castelletti, A., & Kondolf, G. M. (2018a). Improved trade-offs of hydropower and sand connectivity by strategic dam planning in the Mekong. *Nature Sustainability*, *1*(2), 96. DOI: 10.1038/s41893-018-0022-3

Schmitt, R. J., Bizzi, S., Castelletti, A. F., & Kondolf, G. M. (2018b). Stochastic modeling of sediment connectivity for reconstructing sand fluxes and origins in the unmonitored Se Kong, Se San, and Sre Pok tributaries of the Mekong River. *Journal of Geophysical Research: Earth Surface*, *123*(1), 2-25. DOI: 10.1002/2016JF004105

Schmitt, R. J. P., Bizzi, S., Castelletti, A., Opperman, J. J., Kondolf, G.M. (2019). Planning Dam Portfolios for Low Sediment Trapping Shows Limits for Sustainable Hydropower in the Mekong. *Science Advances*, 5(10), eaaw2175. https://doi.org/10.1126/sciadv.aaw2175

Schumm, S. A. (1969). River metamorphosis. American Society of Civil Engineers, *Journal of the Hydraulics division*, *95*(1), 255-274.

Schumm, S. A., Harvey, M. D., & Watson, C. C. (1984). *Incised channels: morphology, dynamics, and control*. Water Resources Publications : Littleton, CO.

Schwenk, J., Khandelwal, A., Fratkin, M., Kumar, V., & Foufoula-Georgiou, E. (2017). High spatiotemporal resolution of river planform dynamics from Landsat: The RivMAP toolbox and results from the Ucayali River. *Earth and Space Science*, *4*(2), 46-75.

Scorpio, V., Santangelo, N., & Santo, A. (2016). Multiscale map analysis in alluvial fan flood-prone areas. *Journal of Maps*, *12*(2), 382-393.

Scorpio, V., Surian, N., Cucato, M., Dai Prá, E., Zolezzi, G., & Comiti, F. (2018). Channel changes of the Adige River (Eastern Italian Alps) over the last 1000 years and identification of the historical fluvial corridor. *Journal of Maps*, *14*(2), 680-691.

Serlet, A. J., Gurnell, A. M., Zolezzi, G., Wharton, G., Belleudy, P., & Jourdain, C. (2018). Biomorphodynamics of alternate bars in a channelized, regulated river: An integrated historical and modelling analysis. *Earth Surface Processes and Landforms*, *43*(9), 1739-1756.

Simon, A., & Hupp, C. R. (1986). Channel Evolution in Modified Tennessee Channels. In *Proceedings of the 4th Federal Interagency Sedimentation Conference*, Las Vegas, Nevada. 5-71–5-82.

Slater, L. J., & Singer, M. B. (2013). Imprint of climate and climate change in alluvial riverbeds: Continental United States, 1950-2011. *Geology*, *41*(5), 595-598. DOI: 10.1130/G34070.1

Slater L. J., Singer M. B., & Kirchner J. W. (2015). Hydrologic versus geomorphic drivers of trends in flood hazard. *Geophysical Research Letters* 42:1–7. DOI: 10.1002/2014GL062482

Slater, L.J., Khouakhi, A., Wilby R.L. (2019a). River channel conveyance capacity adjusts to modes of climate variability. *Scientific Reports*, 9:12619, DOI: 10.1038/s41598-019-48782-1

Slater, L.J., Thirel, G., Harrigan, S., Delaigue, O., Hurley, A., Khouakhi, A., Prosdocimi, I., Vitolo, C., & Smith, K. (2019b). Using R in hydrology: a review of recent developments and future directions. *Hydrology and Earth System Sciences*, 23, 2939-2963. DOI: 10.5194/hess-23-2939-2019

Solins, J. P., Thorne, J. H., & Cadenasso, M. L. (2018). Riparian canopy expansion in an urban landscape: Multiple drivers of vegetation change along headwater streams near Sacramento, California. *Landscape and Urban Planning*, *172*, 37-46.

Spada, D., Molinari, P., Bertoldi, W., Vitti, A., & Zolezzi, G. (2018). Multi-Temporal Image Analysis for Fluvial Morphological Characterization with Application to Albanian Rivers. *ISPRS International Journal of Geo-Information*, *7*(8), 314, DOI:10.3390/ijgi7080314.

Spiekermann, R., Betts, H., Dymond, J., & Basher, L. (2017). Volumetric measurement of river bank erosion from sequential historical aerial photography. *Geomorphology*, *296*, 193-208.

Stähly, S., Friedrich, H., & Detert, M. (2017). Size ratio of fluvial grains' intermediate axes assessed by image processing and square-hole sieving. *J. Hydraul. Eng.* 143, 06017005. https://doi.org/10.1061/(asce)hy.1943-7900.0001286

Steeb, N., Rickenmann, D., Badoux, A., Rickli, C., & Waldner, P. (2017). Large wood recruitment processes and transported volumes in Swiss mountain streams during the extreme flood of August 2005. *Geomorphology*, *279*, 112-127.

Steffen, W., Crutzen, P.J., & McNeill, J.R.. (2007). The Anthropocene: are humans now overwhelming the great forces of nature? *AMBIO: A Journal of the Human Environment* 16(8), 614-621.

Stover, S. C., & Montgomery, D. R. (2001). Channel change and flooding, Skokomish River, Washington. *Journal of Hydrology*, *243*(3-4), 272-286. DOI: 10.1016/S0022-1694(00)00421-2

Straatsma, M. W., & Baptist, M. J. (2008). Floodplain roughness parameterization using airborne laser scanning and spectral remote sensing. *Remote Sensing of Environment*, *112*(3), 1062-1080.

Surian, N., & Rinaldi, M. (2003). Morphological response to river engineering and management in alluvial channels in Italy. *Geomorphology*, *50*(4), 307-326.

Surian, N., Ziliani, L., Comiti, F., Lenzi, M. A., & Mao, L. (2009). Channel adjustments and alteration of sediment fluxes in gravel-bed rivers of North-Eastern Italy: potentials and limitations for channel recovery. *River Research and Applications*, *25*, 551-567.

Surian, N., Barban, M., Ziliani, L., Monegato, G., Bertoldi, W., & Comiti, F. (2015). Vegetation turnover in a braided river: frequency and effectiveness of floods of different magnitude. *Earth Surface Processes and Landforms*, *40*(4), 542-558.

Tamminga, A. D., Eaton, B. C., & Hugenholtz, C. H. (2015). UAS-based remote sensing of fluvial change following an extreme flood event. *Earth Surface Processes and Landforms*, *40*(11), 1464-1476. https://doi.org/10.1002/esp.3728

Tangi, M., Schmitt, R., Bizzi, S., & Castelletti, A. (*2019*). The CASCADE toolbox for analyzing river sediment connectivity and management. *Environmental Modelling and Software*, 119, 400-406, https://doi.org/10.1016/j.envsoft.2019.07.008

Tauro, F., Olivieri, G., Petroselli, A., Porfiri, M., & Grimaldi, S. (2016). Flow monitoring with a camera: A case study on a flood event in the Tiber River. *Environmental monitoring and assessment*, *188*(2), 118. doi:10.1007/s10661-015-5082-5

Tauro, F., Selker, J., Van De Giesen, N., Abrate, T., Uijlenhoet, R., Porfiri, M., ... & Ciraolo, G. (2018). Measurements and observations in the XXI century (MOXXI): Innovation and multi-disciplinarity to sense the hydrological cycle. *Hydrological sciences journal*, *63*(2), 169-196. doi:10.1080/02626667.2017.1420191

Tauro, F., Piscopia, R., & Grimaldi, S. (2019). PTV-Stream: A simplified particle tracking velocimetry framework for stream surface flow monitoring. *Catena*, *172*, 378-386. doi:10.1016/j.catena.2018.09.009

Tena, A., Piégay, H., Seignemartin, G., Barra, A., Berger, J.F., Mourier, B., & Winiarski, T. (*in review*). Cumulative effects of channel engineering and bypassing on floodplain terrestrialisation patterns and connectivity.

Thoma, D. P., Gupta, S. C., Bauer, M. E., & Kirchoff, C. E. (2005). Airborne laser scanning for riverbank erosion assessment. *Remote sensing of Environment*, *95*(4), 493-501.

Thorel, M., Piégay, H., Barthelemy, C., Räpple, B., Gruel, C. R., Marmonier, P., ... & Stella, J. C. (2018). Socio-environmental implications of process-based restoration strategies in large rivers: should we remove novel ecosystems along the Rhône (France)?. *Regional environmental change*, *18*(7), 2019-2031. https://doi.org/10.1007/s10113-018-1325-7.

Tomsett, C., & Leyland, J., (2019). Remote sensing of river corridors: A review of current trends and future directions. River Research and Applications. DOI: 10.1002/rra.3479

Tonon, A., Picco, L., Ravazzolo, D., & Lenzi, M. (2014). Using a terrestrial laser scanner to detect wood characteristics in gravel-bed rivers. *Journal of Agricultural Engineering*, *45*(4), 161-167. https://doi.org/10.4081/jae.2014.431

Toone, J., Rice, S. P., & Piégay, H. (2014). Spatial discontinuity and temporal evolution of channel morphology along a mixed bedrock-alluvial river, upper Drôme River, southeast France: Contingent responses to external and internal controls. *Geomorphology*, *205*, 5-16.

Tormos, T., Kosuth, P., Durrieu, S., Dupuy, S., Villeneuve, B., & Wasson, J. G. (2012). Object-based image analysis for operational fine-scale regional mapping of land cover within river corridors from multispectral imagery and thematic data. *International journal of remote sensing*, *33*(14), 4603-4633.

Truksa, T. (2017). Can drones measure LWD?: high resolution aerial imagery and structure from motion as a method for quantifying instream wood. Geological Society of America *Abstracts with Programs*. Vol. 49, No. 6, Paper No. 354-12. doi: 10.1130/abs/2017AM-308662

Ulloa, H., Iroumé, A., Mao, L., Andreoli, A., Diez, S., & Lara, L. E. (2015). Use of remote imagery to analyse changes in morphology and longitudinal large wood distribution in the Blanco River after the 2008 Chaitén volcanic eruption, southern Chile. *Geografiska Annaler: Series A, Physical Geography*, *97*(3), 523-541.

Van Der Knijff, J. M., Younis, J., & De Roo, A. P. J. (2010). LISFLOOD: a GIS-based distributed model for river basin scale water balance and flood simulation. *International Journal of Geographical Information Science*, *24*(2), 189-212. DOI: 10.1080/13658810802549154

Vauclin, S., Mourier, B., Seignemartin, G., Tena, A., Develle, A.L., Piégay, H., Berger, J.F., Winiarski, T. (*in review*). Characterizing the infrastructure-induced legacy sediments by a combined geophysical and coring approach.

Vázquez-Tarrío, D., Borgniet, L., Liébault, F., & Recking, A. (2017). Using UAS optical imagery and SfM photogrammetry to characterize the surface grain size of gravel bars in a braided river (Vénéon River, French Alps). *Geomorphology*, *285*, 94-105. DOI: https://doi.org/10.1016/j.geomorph.2017.01.039

Vericat, D., Brasington, J., Wheaton, J., & Cowie, M. (2009). Accuracy assessment of aerial photographs acquired using lighter-than-air blimps: low-cost tools for mapping river corridors. *River Research and Applications*, *25*(8), 985-1000.

Vericat, D., Wheaton, J. M., & Brasington, J. (2017). Revisiting the morphological approach: opportunities and challenges with repeat high-resolution topography. In: Tsutsumi D, Laronne JB (eds) *Gravel-Bed Rivers Processes and Disasters*. John Wiley and Sons: Chichester; 121-158.

Wackrow R, Chandler JH. (2008). A convergent image configuration for DEM extraction that minimises the systematic effects caused by an inaccurate lens model. The Photogrammetric Record **23**, 6–18.

Wackrow R, Chandler JH. (2011). Minimising systematic error surfaces in digital elevation models using oblique convergent imagery. The Photogrammetric Record **26**, 16–31.

Wadell, H., (1932). Volume, shape, and roundness of rock particles. *Journal of Geology*, 40:443-51.

Wawrzyniak, V., Räpple, B., Piégay, H., Michel, K., Parmentier, H., & Couturier, A. (2014). Analyse multi-temporelle des marges fluviales fréquemment inondées à partir d'images satellites Pléiades. *Revue Française de Photogrammétrie et de Télédétection.*

Wawrzyniak, V., Piégay, H., Allemand, P., Vaudor, L., Goma, R., & Grandjean, P. (2016). Effects of geomorphology and groundwater level on the spatio-temporal variability of riverine cold water patches assessed using thermal infrared (TIR) remote sensing. Remote Sensing of Environment, 175, 337-348. https://doi.org/10.1016/j.rse.2015.12.050

Westaway RM, Lane SN, Hicks DM. (2003). Remote survey of large-scale braided, gravel-bed rivers using digital photogrammetry and image analysis. International Journal of Remote Sensing **24**, 795–815.

Wheaton, J.M., Brasington, J., Darby, S.E., Sear, D.A. (2010). Accounting for Uncertainty in DEMs from Repeat Topographic Surveys: Improved Sediment Budgets. *Earth Surface Processes and Landforms*, 35(2), 136-156.

Wheaton, J.M., Fryirs, K.A., Brierley, G., Bangen, S.G., Bouwes, N., O'Brien, G., (2015). Geomorphic mapping and taxonomy of fluvial landforms. Geomorphology 248, 273–295. https://doi.org/10.1016/j.geomorph.2015.07.010

Williams, R. D., Brasington, J. , Vericat, D. and Hicks, D. M. (2014), Hyperscale terrain modelling of braided rivers: fusing mobile terrestrial laser scanning and optical bathymetric mapping. *Earth Surface Processes and Landforms, 39*: 167-183. doi:10.1002/esp.3437

Winterbottom SJ, Gilvear DJ. (1997). Quantification of channel bed morphology in gravel-bed rivers using airborne multispectral imagery and aerial photography. Regulated Rivers: Research & Management: An International Journal Devoted to River Research and Management **13**, 489–499.

Woodget AS, Carbonneau PE, Visser F, Maddock IP. (2015). Quantifying submerged fluvial topography using hyperspatial resolution UAS imagery and structure from motion photogrammetry. Earth Surface Processes and Landforms **40**, 47–64.

Woodget, A.S., Austrums, R., (2017). Subaerial gravel size measurement using topographic data derived from a UAV-SfM approach. Earth Surf. Process. Landforms 42, 1434–1443. https://doi.org/10.1002/esp.4139

Woodget, A.S., Fyffe, C., Carbonneau, P.E., (2018). From manned to unmanned aircraft: Adapting airborne particle size mapping methodologies to the characteristics of sUAS and SfM. Earth Surface Processes and Landforms 43, 857–870. https://doi.org/10.1002/esp.4285

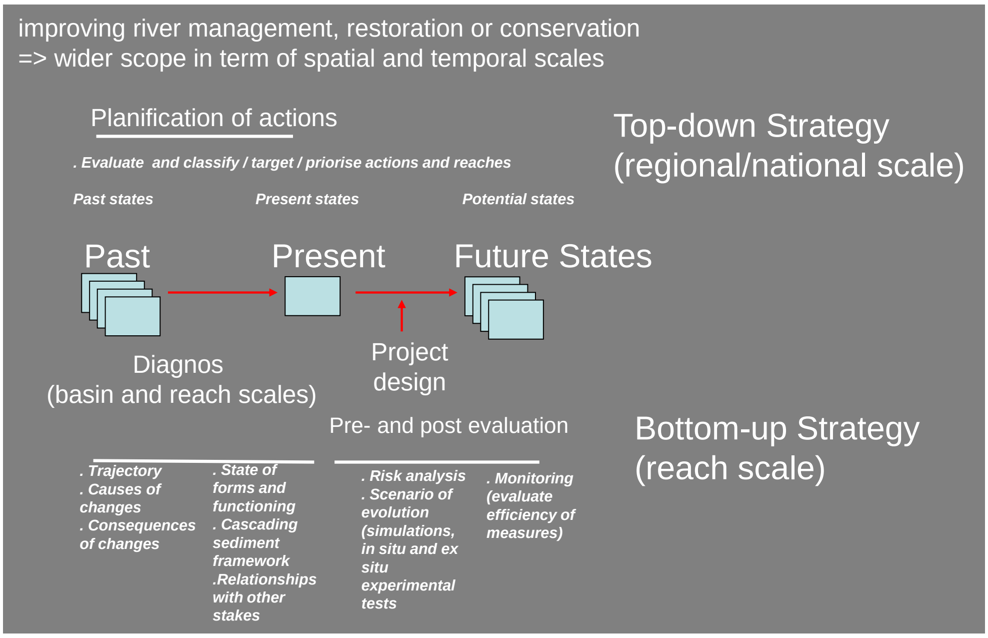
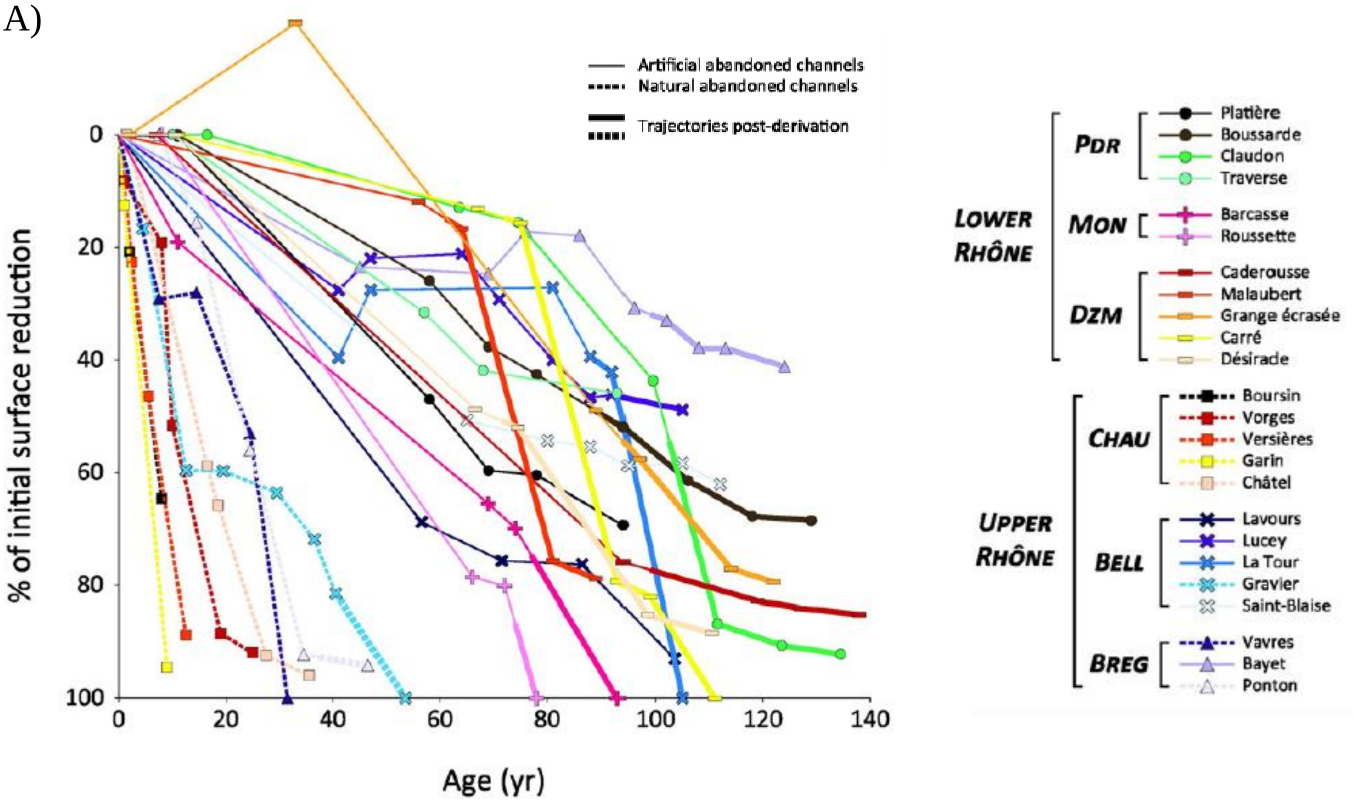


Figure 1. General framework of geomorphic studies: diagnosis and project appraisal, top-down and bottom-up strategies (source: Piégay et al. 2016, chapter 22)

A)



Artificial abandoned channels
Natural abandoned channels
Trajectories post-derivation
% of initial surface reduction
Age (yr)
0
20
40
60
80
100
0
20
40
60
80
100
120
140
LOWER RHÔNE
PDR
Platière
Boussarde
Claudon
Traverse
MON
Barcasse
Roussette
DZM
Caderousse
Malaubert
Grange écrasée
Carré
Désirade
UPPER RHÔNE
CHAU
Boursin
Vorges
Versières
Garin
Châtel
BELL
Lavours
Lucey
La Tour
Gravier
Saint-Blaise
BREG
Vavres
Bayet
Ponton

B)

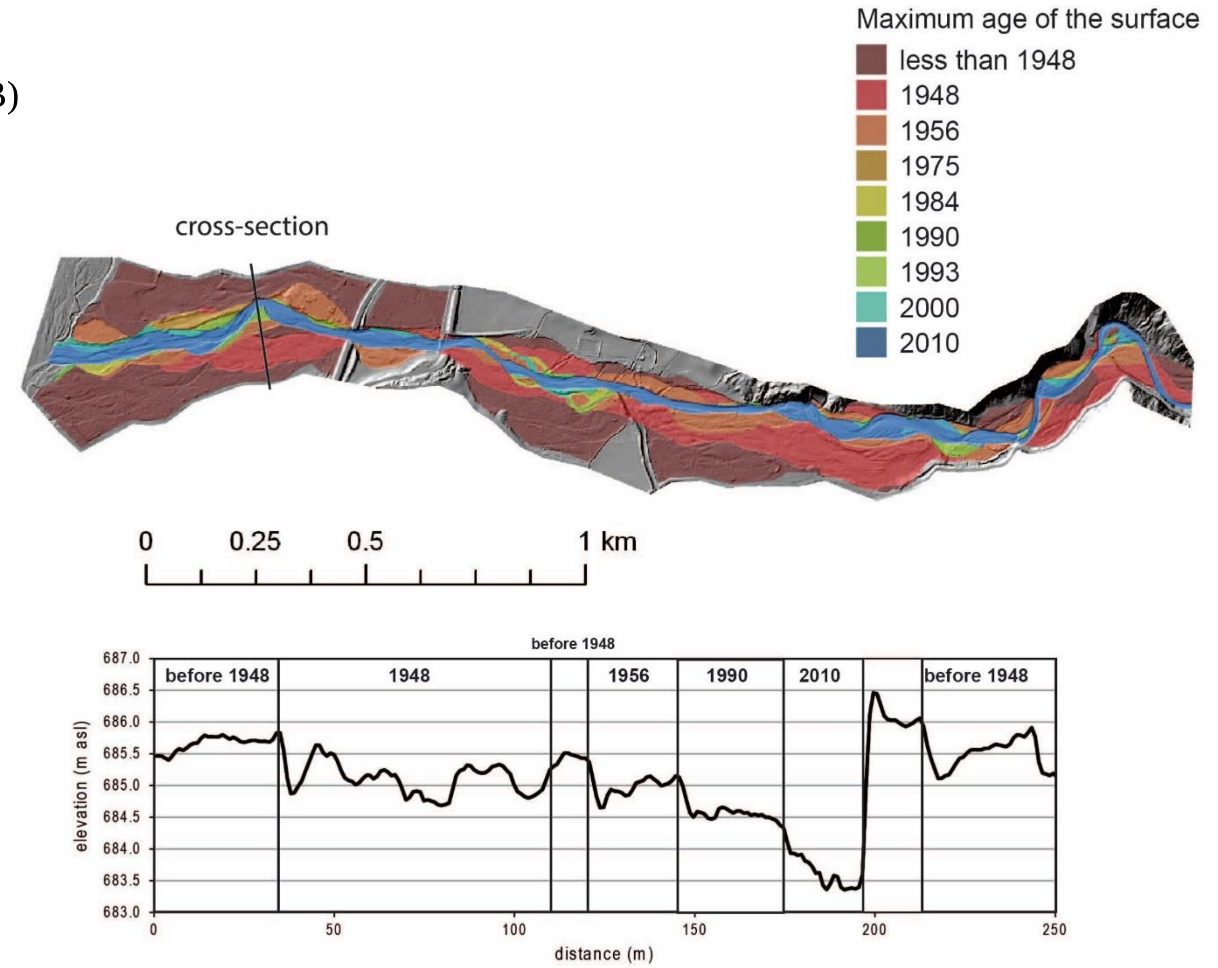


Figure 2. Temporal evolution of surface areas through time based on a series of aerial photographs: (A) example of the terrestrialisation of the natural (dashed line) and artificial (thick line) abandoned channels of the Rhône River – Grange Ecrasée is the only one case of expansion right after cut-off and then shrinking (Source: Figure 1, Dépret et al. 2017, Geomorphology) (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

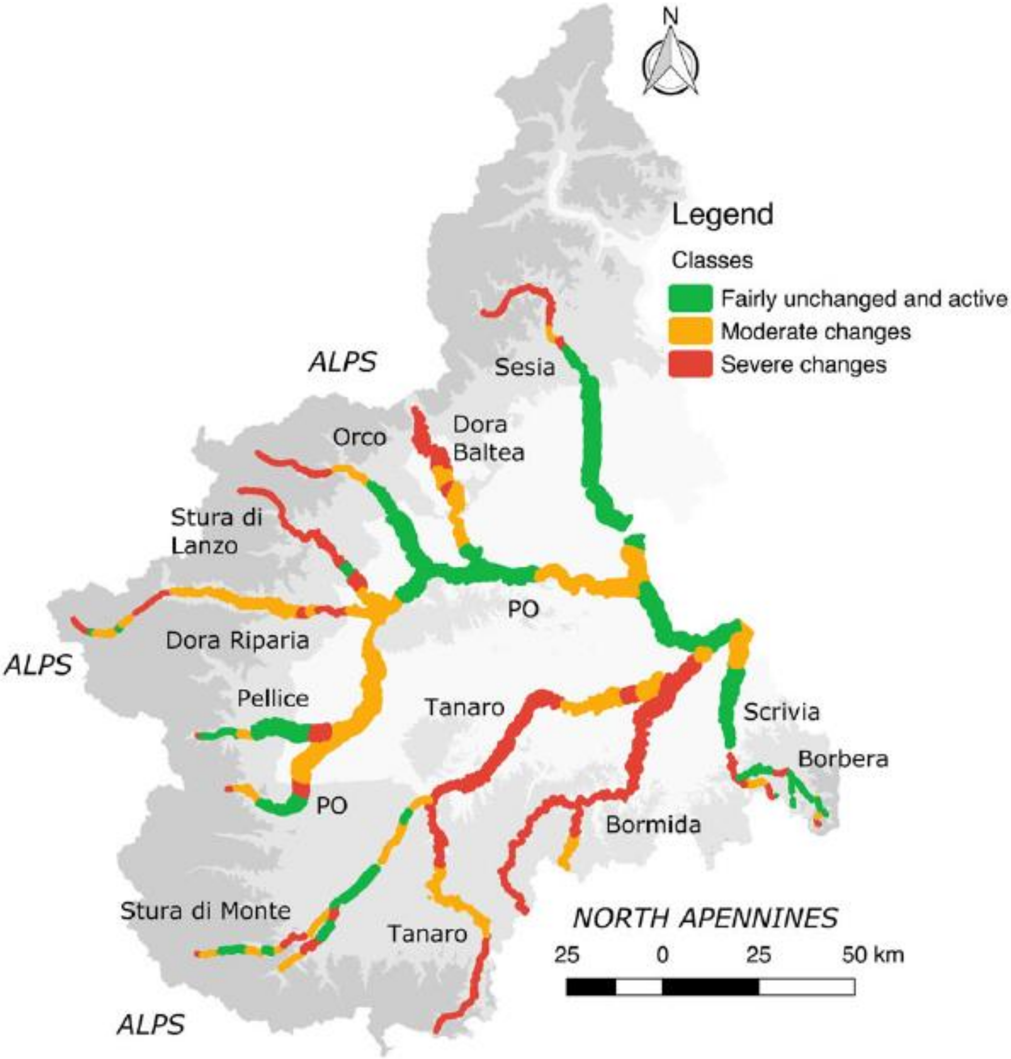


Figure 3. Classes of channel changes combining incision and narrowing based on regional LiDAR, aerial photos and field/archived data to established reference: severe changes indicate significant narrowing (>50-100% of their current width) and riverbed incision (2-5 m) over the last century, moderate changes indicate mostly river reaches that show substantial narrowing and moderate channel incision (source: Figure 12, Bizzi et al., 2018 in ESPL)

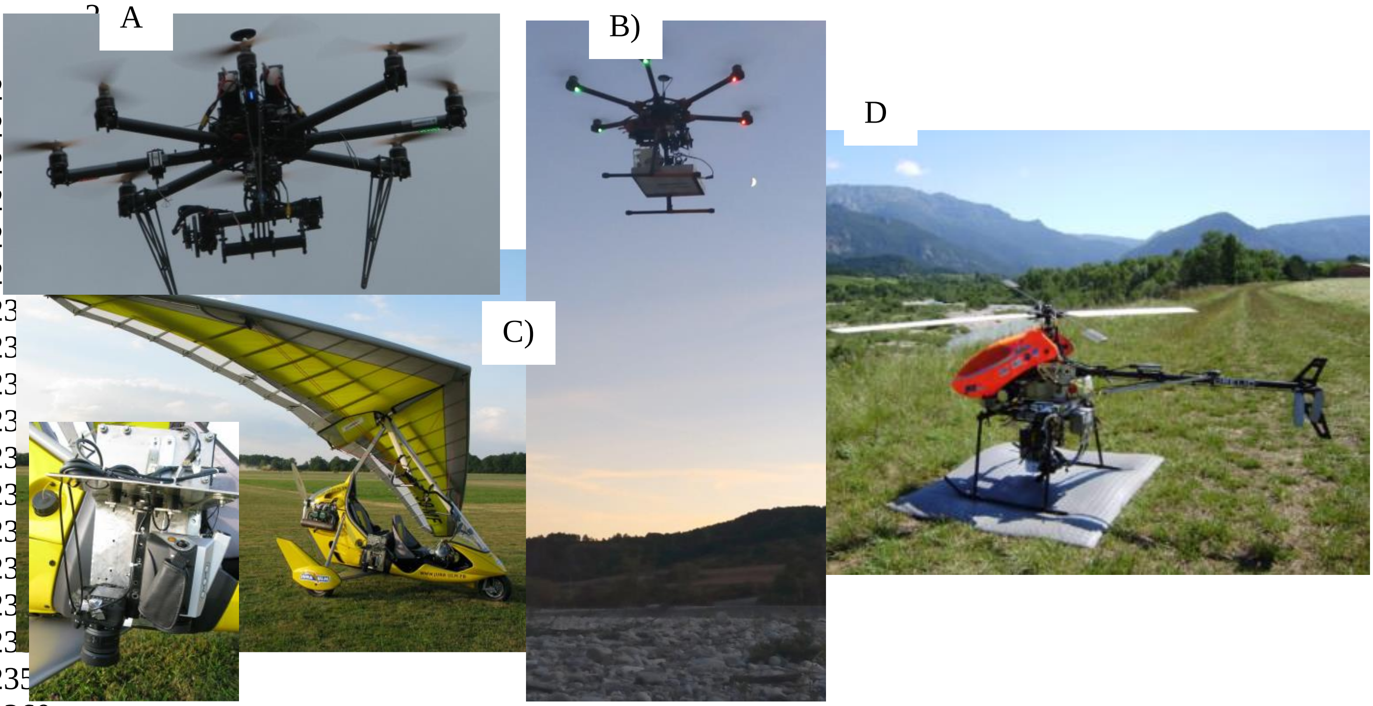


Figure 4. Example of platforms used by scientific teams to acquire hyperspatial imagery : A) Octocopter ; B) Hexacopter equipped with an active RFID antenna; C) Ultralight trike equipped with RGB and thermal cameras; D) Unmanned Control Helicopter (Sources : A) Franck Perret ; B) Mathieu Cassel; C) Baptiste Marteau and D) Kristell Michel)

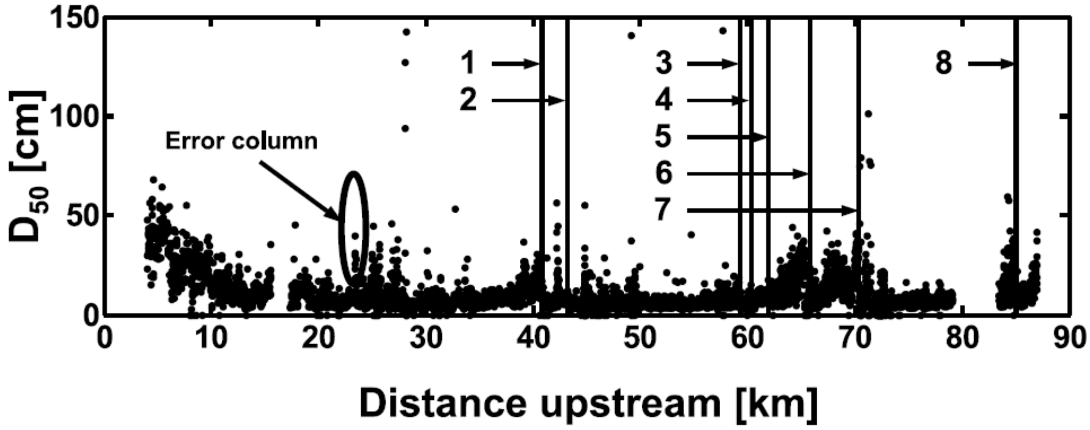


Figure 5. Long profile of median grain size over 80 km of the Sainte Marguerite River, Québec from image processing and showing link cutoff points (vertical lines), numbered 1–8 as determined by Davey and Lapointe (unpublished report, 2004) and an example of an ‘‘error column’’structure caused by glare at the water surface (Source : Figure 5. Carbonneau et al., 2005).

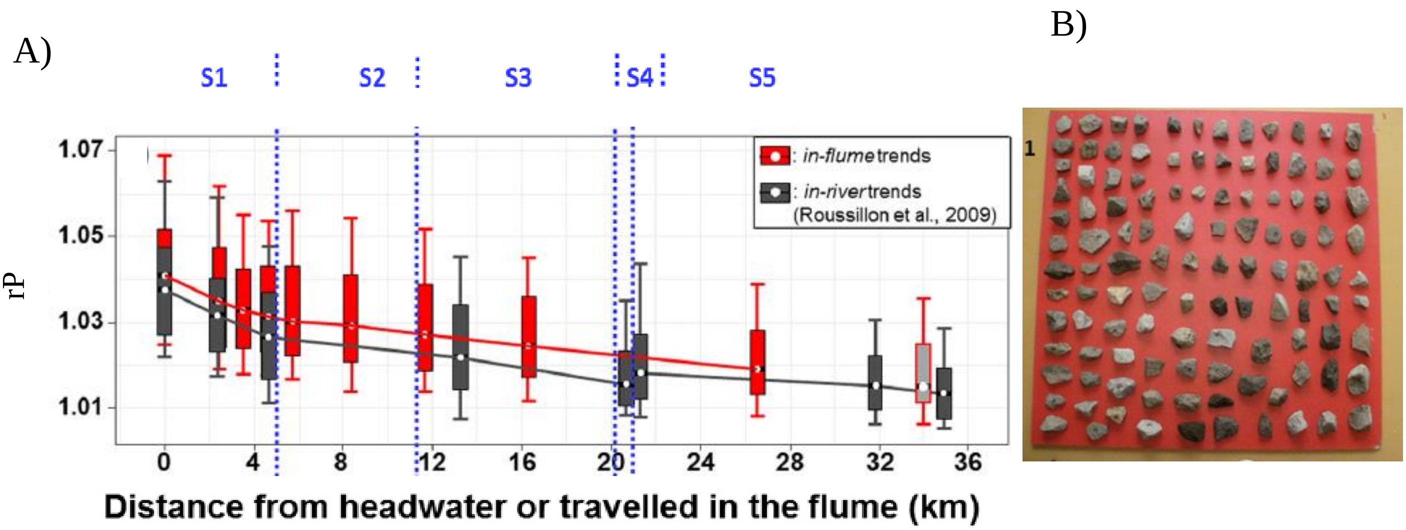


Figure 6. (A) Evolutions of the ratios of perimeters rP according to the distance travelled through 36 km from the headwater of Progo river (Indonesia) (dark grey) or in an annular flume (red). rP = Pg/Pe with Pg the pebble perimeter and Pe the ellipse perimeter, both having the same surface area. The single clear grey boxplot with red borders represents values 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 percentiles values. White circles represent median values. (B) Example of picture of angular pebbles taken for roundness analysis. (Source: Cassel et al., 2018, Figure 11 and Figure 3).

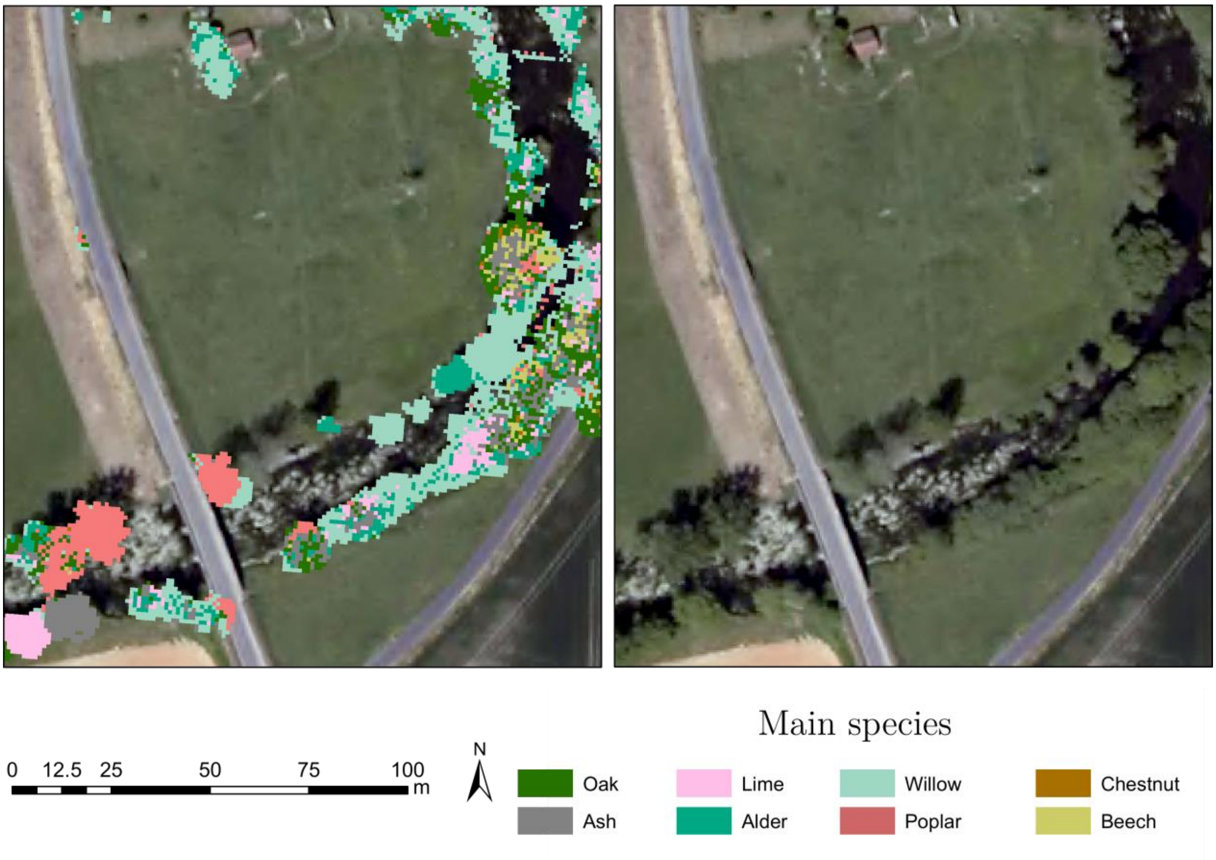


Figure 7. Riparian genuses map obtained from LiDAR data and tree morphological patterns (Sélune River, western France). Tree crown morphology and internal structure indicators were computed from the 3D points clouds of two surveys (summer and winter; n = 144 indicators) and the most discriminant indicators 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 3 genuses to 50% for 8 genuses. With 8 genuses, the identification remains a challenge as for one tree crown predicted pixels can be mixed (Source: Ba et al., 2019)

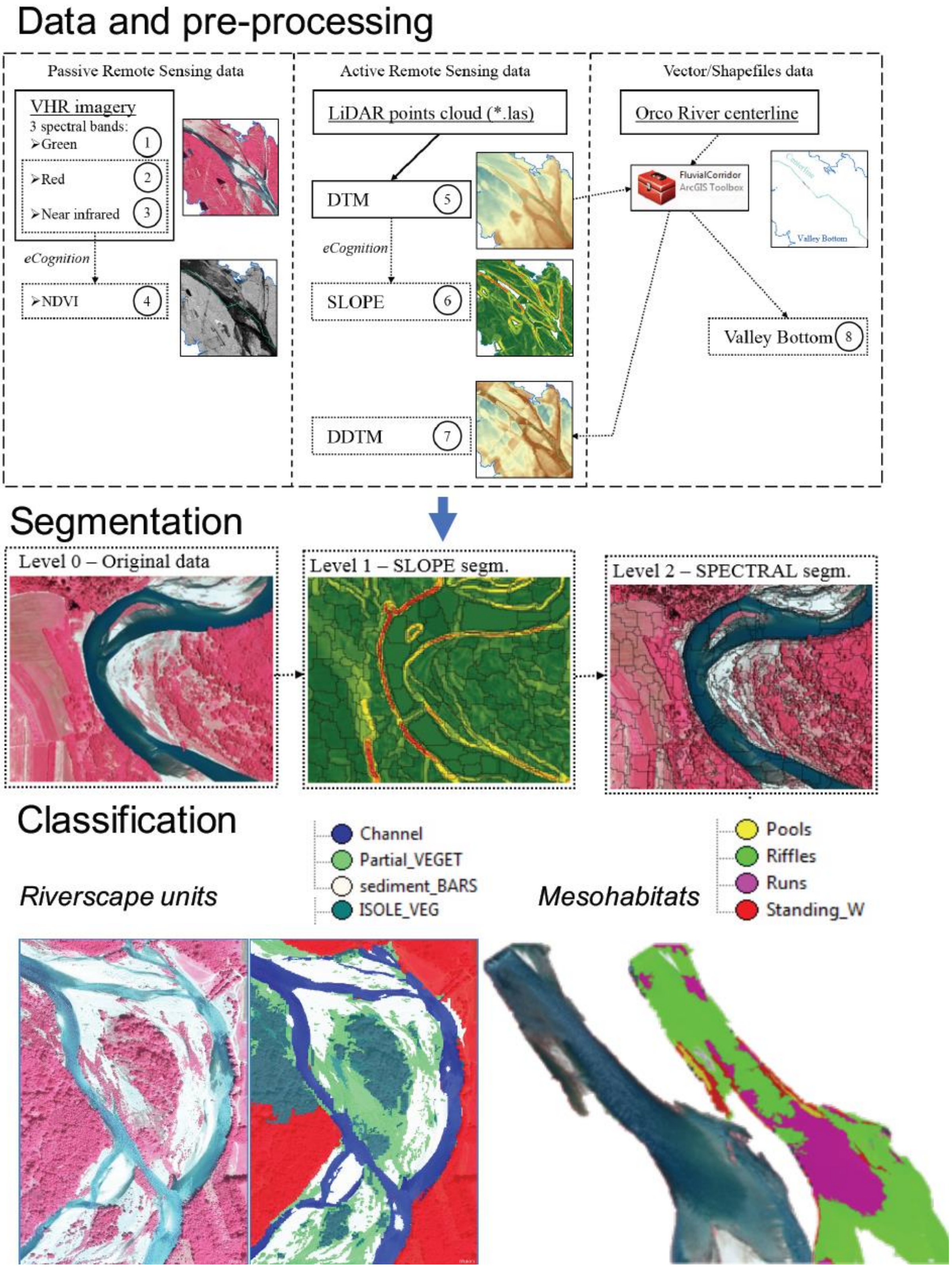


Figure 8. Workflow of the multilevel, object-based methodology developed for the classification of riverscape units and in-stream mesohabitats. Top row shows data type used (multispectral and Lidar derived DTM); central row describes the OBIA steps to derive topographically and spectrally homogenous units; the bottom row displays classification results for riverscape units (on the left) and mesohabitats (on the right). (Source: Demarchi et al. 2016 Figure 5)

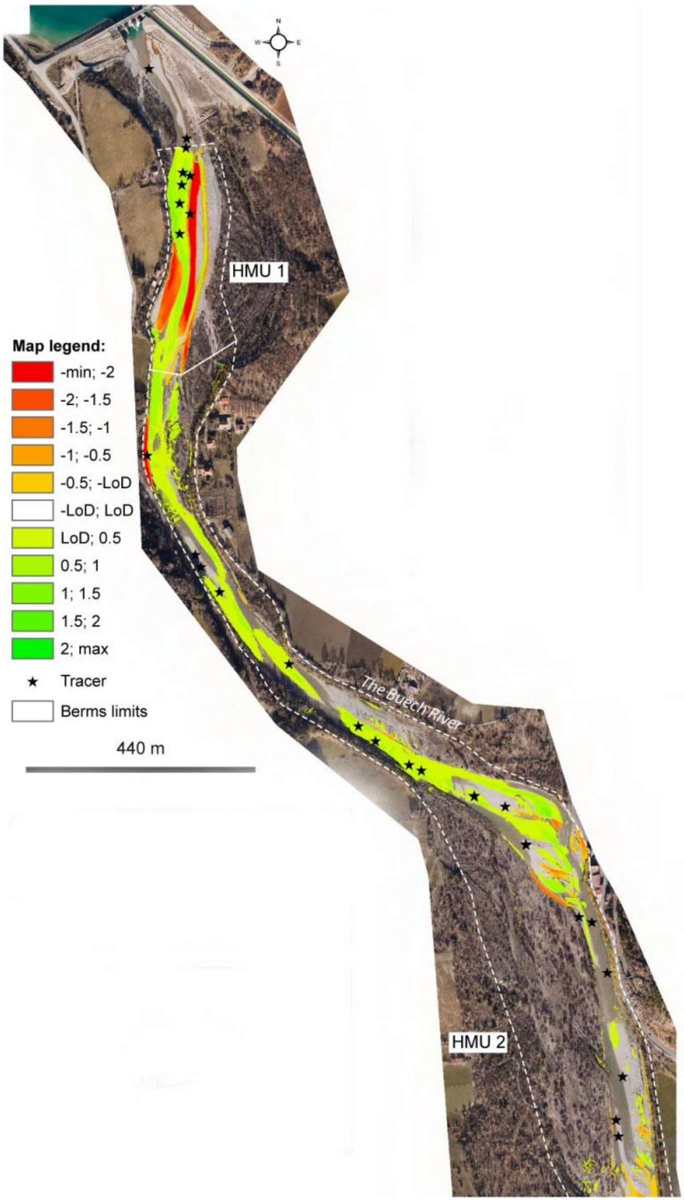


Figure 9. Monitoring of sediment wave propagation following a gravel replenishment operation downstream of a dam in the Buëch River (Southern French Prealps), using repetitive airborne LiDAR surveys and UHF active RFID tags (source: Brousse et al, online); the combination of HR topographic differencing before and after a 5-yr flood and bedload tracing successfully allow to detect the propagation of the artificially-induced sediment wave, with a front located at 2.5 km from the dam

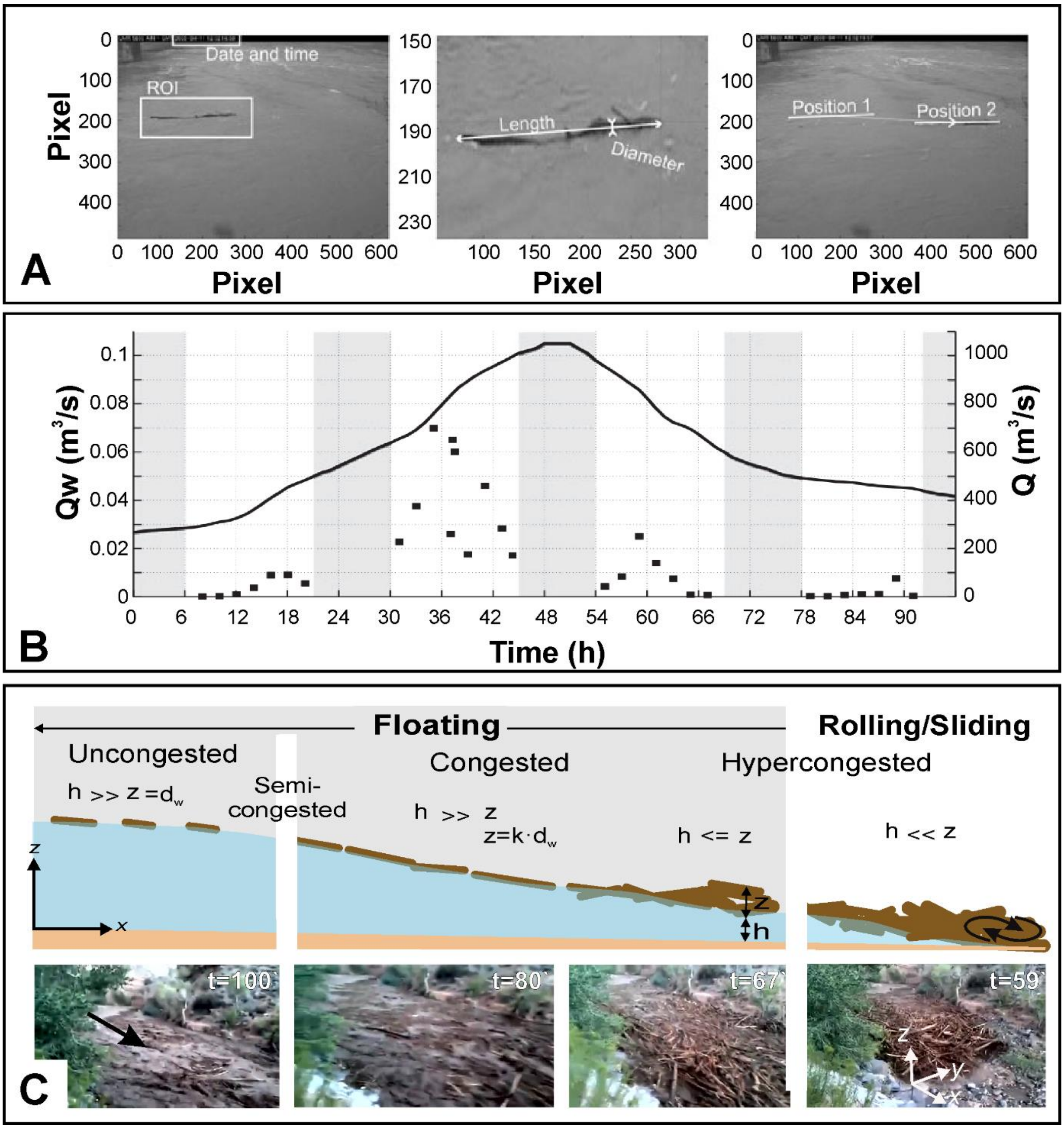


Figure 10: (A) Wood detection procedure using a video camera in the Ain River, France. Images show the region of interest (ROI) based on a visual detection of wood including measurement of date and time from time stamp, the precise location of end and side points to define the piece length, diameter, 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 April 10–13, 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, US) at different times (t), h: water depth and z: wood flow depth; d_w: wood piece diameter; k: coefficient >1 (Modified from Ruiz-Villanueva et al., 2019).

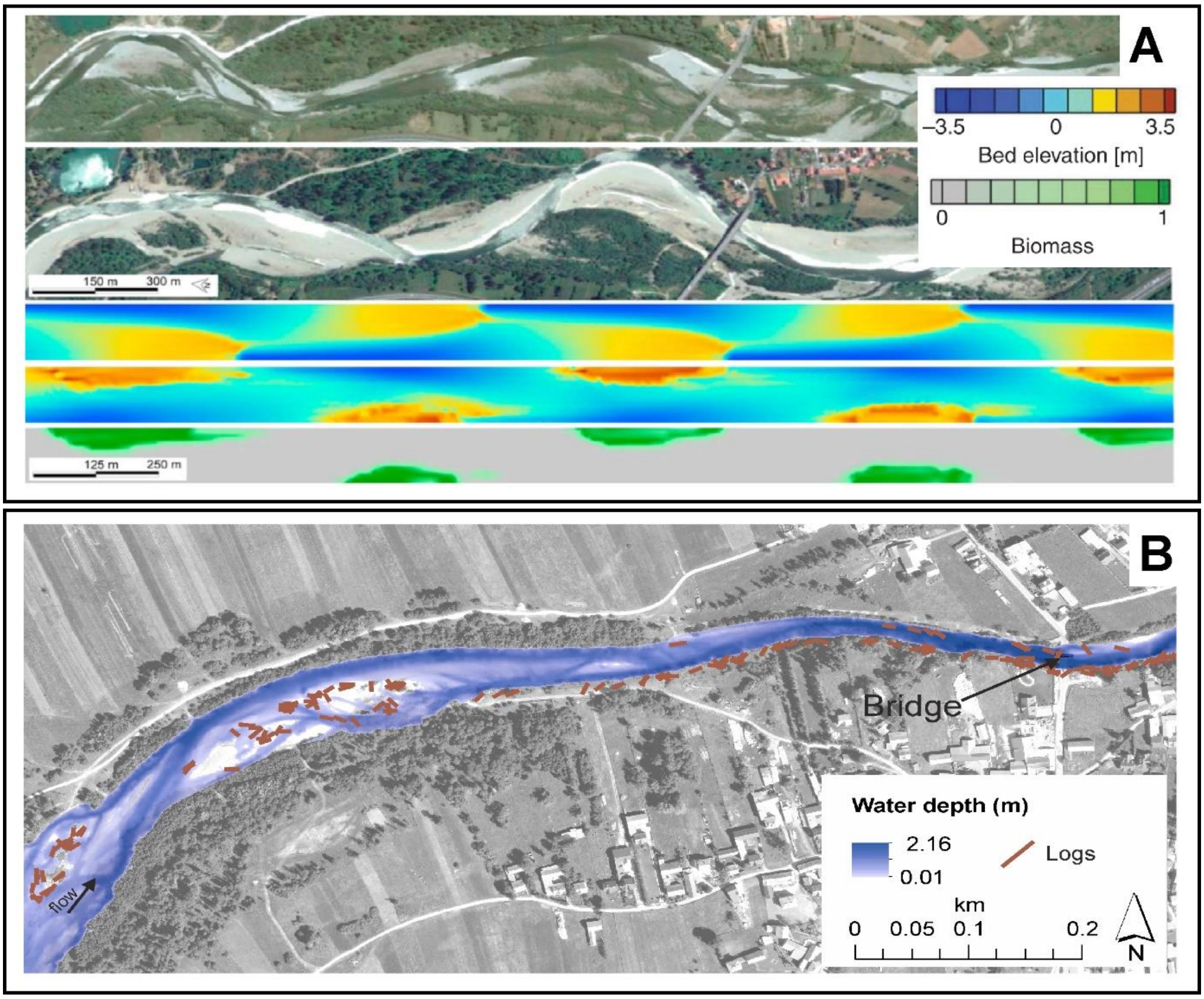


Figure 11: (A) Aerial images of the Magra River near Aulla (Italy) in 2007 (up) and in 2011 (down) and bed topography before a simulated flood sequence, after four floods and simulated biomass distribution (From Bertoldi et al., 2014).(B) Simulated water depth and logs deposited along the Czarny Dunajec River reach at a discharge of $28m^3$/s. From Ruiz-Villanueva et al., 2017.

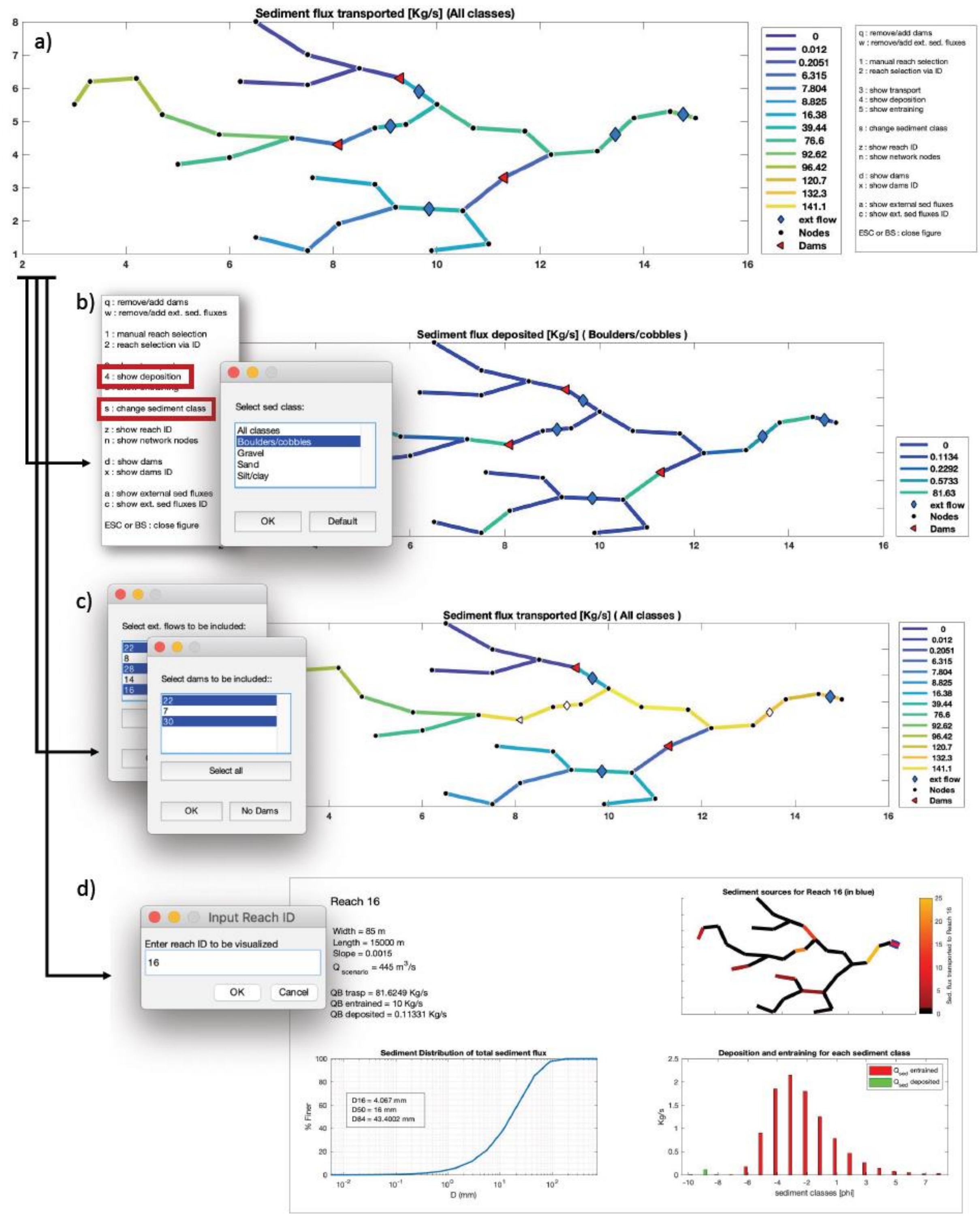


Figure 12. Examples of plots obtained from CASCADE toolbox (source: Tangi et al, 2019). The tool allows analysing various properties of sediment connectivity in an interactive manner. Panel a shows the total sediment transported in Kg/s in the network. b visualizes patterns of deposition for a single sediment class out of the 18 considered in the model (in this case boulders/cobbles). c shows the changes in total sediment transport caused by the removal of one dam and two external sediment flows. d shows an 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.

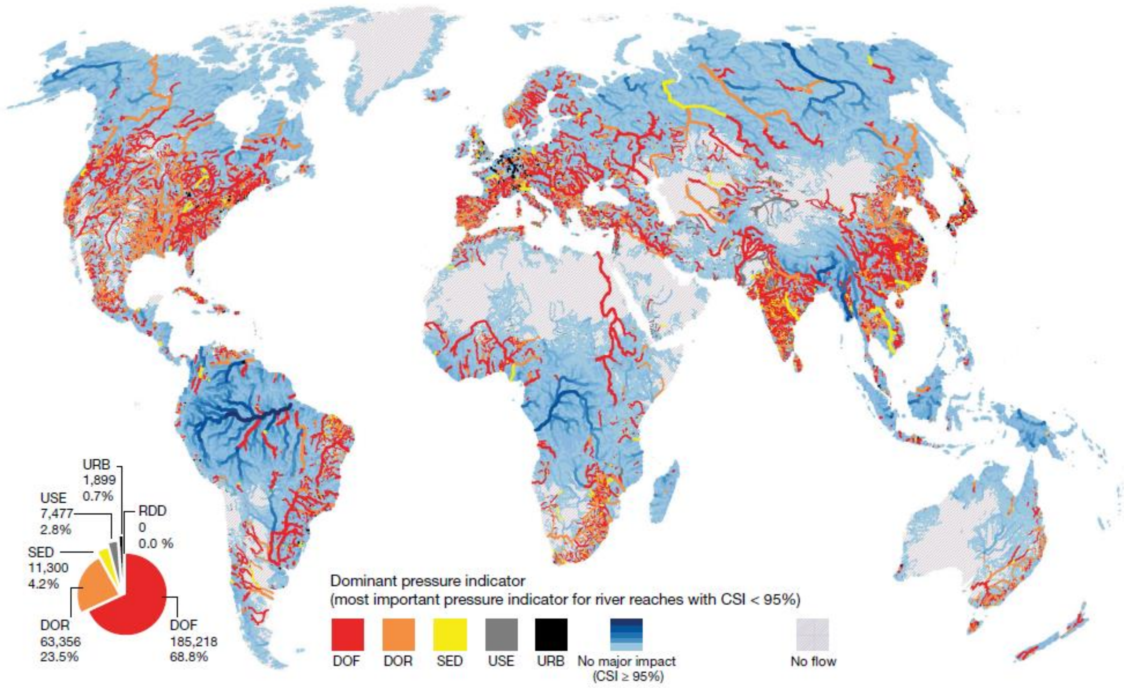


Figure 13. Dominant pressure indicator for global river reaches below a given Connectivity Status Index (CSI) threshold (95%). Pressure indicators include the DOF (degree of fragmentation), DOR (degree of regulation), SED (sediment trapping), USE (consumptive water use) and URB (urban areas). The inset shows the number and proportion of river reaches per dominant pressure indicator at the global scale. (Source: Grill et al., 2019; Figure 2)

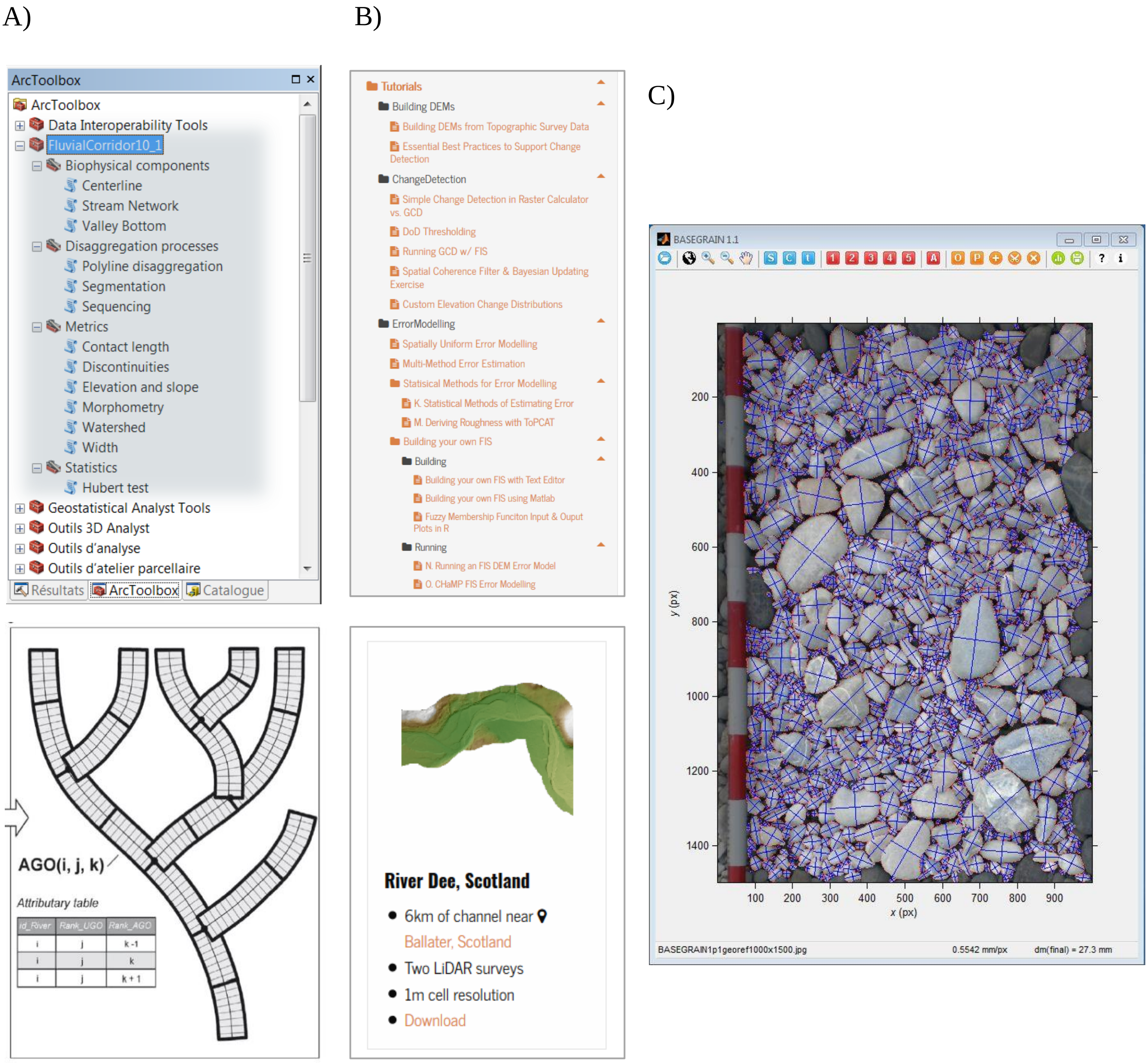


Figure 14. Example of tools/interfaces available online to measure characters of fluvial corridors : A) The Fluvial Corridor Toolbox – FCT - within the ArcGIS Arc Toolbox (Roux et al. 2015) and view of generic spatial units for characterizing aggregated geographical objects at the network-scale (https://github.com/EVS-GIS/Fluvial-Corridor-Toolbox-ArcGIS); B) website views (tutorial and dataset example) of the Geomorphic Change Detection software (http://gcd.riverscapes.xyz/) (Wheaton et al., 2010a); and 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) (Detert et Weitbrecht, 2012)