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ESEX Commentary

Recent remote sensing applications for hydro and morphodynamic monitoring and modelling

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ESPL

Earth Surface Processes and Landforms

ABSTRACT: It is not new to recognize that data from remote sensing platforms is transforming the way we characterize and analyse our environment. The ability to collect continuous data spanning spatial scales now allows geomorphological research in a data rich environment and this special issue [coming just eight years after the 2010 special issue of *Earth Surface Processes and Landforms* (ESPL) associated with the remote sensing of rivers] highlights the considerable research effort being made to exploit this information, for studies of geomorphic form and process. The 2010 special issue on the remote sensing of rivers noted that fluvial remote sensing articles made up some 14% of the total river related articles in ESPL. A similar review of articles up to 2017 reveals that this figure has increased to around 25% with a recent proliferation of articles utilizing satellite-based data and structure from motion photogrammetry derived data. It is interesting to note, however that many studies published to date are proof of concept, concentrating on confirming the accuracy of the remotely sensed data at the expense of generating new insights and ideas on fluvial form and function. Data is becoming ever more precise and researchers should now be concentrating on analysing these early data sets to develop increased geomorphic insight, to challenge existing paradigms and to advance geomorphic science. The prospect of this occurring is increased by the fact that many of the new remote sensed platforms allow accurate spatial data to be collected cheaply and efficiently, reducing the need for substantial research funding to advance river science. Fluvial geomorphologists have never before been in such a liberated position. As techniques and analytical skills continue to improve it is inevitable that the prediction that remotely sensed data will revolutionize our understanding of geomorphological form and process will prove true, altering our ideas on the very nature of system functioning in the process. © 2018 The Authors. Earth Surface Processes and Landforms published by John Wiley & Sons Ltd.

KEYWORDS: remote sensing; hydromorphology; morphodynamic; monitoring; modelling

Introduction

Remote sensing is leading to a radical transformation in the way we map and analyse our environment (Marcus and Fonstad, 2010) with new instrumentation and software allowing for the collection and analysis of continuous data spanning spatial scales previously unachievable using earlier technologies. We can now research in a data rich environment and are beginning to exploit this transformation in available integrated scales of information, into new understanding of geomorphic form and process, helping to truly cover the range of fluvial structure and function advocated by Lane *et al*. (1994).

The 2010 special issue of *Earth Surface Processes and Landforms* (ESPL) associated with the remote sensing of rivers contained 12 seminal articles on the emerging use of remote sensing platforms in geomorphology covering system structure, evolution and process measurement. In their review article the editors concluded that 'the time for more widespread application of river remote sensing techniques is now' (Marcus and Fonstad, 2010, p. 1867). Then Marcus and Fonstad (2010) noted that fluvial remote sensing articles made up some 14% of the total river related articles in ESPL. Seven years have passed during which time geomorphological research utilizing remotely sensed data has increased further with improvements in data acquisition and processing facilitating the analysis of increasingly detailed and complex environmental data sets. Table I illustrates the publication trend since 2010 reviewing the type of remote sensing employed. What is immediately striking is that around a quarter of those papers published in the journal make use of remote sensing of river environments, a significant increase over only seven years. Also of note are the recent proliferation of articles utilizing unmanned aerial platforms for data collection and structure from motion photogrammetry.

Table I. Summary of remote sensing driven fluvial research in *Earth Surface Processes and Landforms* (ESPL) since 2010.

Year	Total papers	Total river related papers	% Contributions	Satellite	Drone/ structure from motion	Photogrammetry	Total station/ rangefinder	dGPS	Terrestrial laser scanning	Airborne laser scanning	Aerial photographs	Mapping	Optical/ hyperspectral	Other remote sensing	Particle imaging	Total environment simulator	Video
2011	137	34	25	2			1	1	2		4		1	2	1		
2012	128	36	28	8				3	3	3	5		2	2			
2013	136	35	26	3		1	1	1	4	3	5		3	1		1	
2014	154	42	27		1		1	1	1	4	1	2	3				
2015	148	50	34	4	5	2	1	2	3	2	4		4	1			
2016	164	50	30	9	1	1	2	3	3	8	5	1	1	2			
2017	177	74	42	4	8	8	1	1	3	4	4		5	1			1

Note: dGPS, differential global positioning system.

Since the ESPL review article by Marcus and Fonstad (2010), the general uptake of remote sensing methods in physical geography in general has been reviewed by Tarolli (2014) and for fluvial systems by Carbonneau and Piégay (2012). Gilvear and Bryant (2016) also provide a useful review of satellite-based remotely sensed data. This article leads the special issue on 'Remote sensing applications for hydro and morphodynamic monitoring and modelling' that brings together a series of articles presented at the 11th International Symposium on Ecohydraulics, held in Melbourne, February 2016. It is abundantly clear that Marcus and Fonstad (2010) were correct in their prediction, remotely sensed data are revolutionizing our understanding of geomorphological form and process altering our ideas on the very nature of system functioning as it does so in the process.

Early work

The use of remote sensed data is far from new. What has changed is the type of remote sensed data being used and the manner in which these data have been collected. Some of the earliest use of remote sensed data centred around oblique and aerial photography (see review by Gilvear and Bryant, 2003). Notable early work included elucidating information on alpine glacier retreat (LaChapelle, 1962). In a fluvial context aerial photography has been used to study floodplain geometry (Lewin and Manton, 1975), bank retreat (Williams *et al.*, 1979), historical meander development (Hooke, 1984), and barform change (Warburton *et al.*, 1993). Spaceborne imagery has also proved usable on large rivers with Salo *et al.* (1986) mapping planform movement on the Amazon system.

Since these early studies we have seen the emergence of optical image analysis utilizing parameters such as contrast and spectral signatures to derive a variety of fluvial variables. For example, Hicks *et al.* (2000) used spectral analysis to derive flow depth and Hardy *et al.* (1994) and Winterbottom and Gilvear (1997) used the approach to map hydraulic habitat.

Passive and active laser-based instruments have emerged as a remote sensing tool with light detection and ranging (LiDAR)-based studies (Heritage and Large, 2009). Photogrammetric approaches have evolved, with vertical imagery used to study areas over 1 km^2 (Westaway *et al.*, 2000; Smith *et al.*, 2016), and oblique photogrammetry used to map gravel bar surfaces (Heritage *et al.*, 1998).

Recent Research

Articles published in the 2010 ESPL special issue on fluvial remote sensing reflects well the remote sensing techniques of the time with aerial and terrestrial LiDAR articles dominating and the use of aerial imagery being largely restricted to analysis of optical properties. Table I illustrates clearly how other techniques, most notably those based on photogrammetry have emerged to dominate the literature assisted by the development of small aerial platforms to facilitate the data collection phase.

Optical approaches

Legleiter (2013) mapped river depth from publicly available US National Agricultural Imagery Programme aerial images but found issues with geo-referencing errors and a coarser spatial resolution. Optical approaches have moved towards using image texture and reflectance spectra as a discriminator to differentiate and map fluvial character and Belletti *et al.* (2015) review optical approaches to classify river hydromorphology. A detailed investigation of bed sedimentology has been achieved at the catchment scale using image texture analysis to generate a map of median grain size for submerged and dry fluvial surfaces along an 80 km length of the Sainte-Marguerite River, Québec, Canada (Carbonneau *et al.*, 2004). Flood inundation area has been mapped using Spaceborne imagery (Pierdicca *et al.*, 2013) including Landsat (Feyisa *et al.*, 2014), although issues have been shown to arise with emergent vegetation (Silva *et al.*, 2008).

Multispectral imaging has been exploited by Wright *et al.* (2000) to map morphological units and Legleiter (2012) utilized similar data to derive channel bathymetry as part of a combined study with LiDAR, reporting that pool depths were generally underestimated with turbidity strongly influencing the data quality. Multi feature classification has also been attempted for river hydromorphology using high-resolution small unmanned air vehicle (sUAV) imagery (Casado *et al.*, 2015), whilst Bentley *et al.* (2016) utilized Google Earth and Bing aerial imagery to generate long-reach digital elevation models (DEMs) for two-dimensional (2D) hydraulic habitat modelling.

Imagery has also been used to infer process. Pioneering early work by Mertes *et al.* (1993) estimated suspended sediment concentrations for the Amazon floodplain after reflectance correction and Gomez *et al.* (1995) derived suspended sediment characteristics for the Mississippi using satellite data. More recently Bywater-Reyes *et al.* (2017) quantified the impact of forestry operations on suspended sediment yields from five headwater sub-catchments of the Trask River, Oregon.

LiDAR

Aerial LiDAR has increased our understanding of earth systems most commonly over landscape scales achieving decimetre scale vertical elevation accuracies (Smith and Vericat, 2014). The application of aerial LiDAR to fluvial systems saw a rapid increase from around 2000 due to the wider availability of hardware, and the introduction of terrestrial LiDAR systems (for reviews see Hohenthal *et al.*, 2011; Milan and Heritage, 2012; Heritage and Large, 2009). Aerial LiDAR has the advantage over photography in that it can penetrate vegetation to provide information below the canopy (Glennie *et al.*, 2013), although penetration can fail where vegetation is too dense (Malinowski et al., 2016). Aerial LiDAR data is being used in a range of fluvial applications including (1) hydrogeomorphic assessment at the reach (Charlton *et al.*, 2003) and catchment-scale (Biron *et al.*, 2013), (2) detection and quantification of logjams in lowland rivers (Abalharth *et al.*, 2015), (3) parameterization of spatial vegetation roughness on floodplains for 2D hydraulic modelling (e.g. Bertoldi *et al.*, 2011; Straatsma and Baptist, 2008; Antonarakis *et al.*, 2008; Abu-Aly *et al.*, 2014), (4) delineation of water surface and flood innundation extent based on laser pulse reflectance values (Crasto *et al.*, 2015; Malinowski, 2016), and (5) provision of boundary conditions for modelling the geomorphic impacts of catastrophic events (Thompson and Croke, 2013).

Sequential aerial LiDAR surveys are also increasingly being used to (6) detect morphological changes in rivers (e.g. Lallias-Tacon *et al.*, 2017; Nelson and Dubé, 2016; Thompson *et al.*, 2016; Milan et al., 2018). Work has also integrated historical aerial photographs and LiDAR to extend the historic DEM time-series, allowing a much longer record of historical spatial patterns of morphological change to be assessed (De Rose and Basher, 2011).

Full waveform LiDAR has been tested (Schofield *et al.*, 2016) and used extensively in forest remote sensing (Wulder *et al.*, 2012). In a fluvial context, Kinzel *et al.* (2007) surveyed a shallow, braided, sand-bedded river system using an experimental terrestrial algorithm to successfully approximate the position of the river bed. Mean signed errors of 0.18 m were reported across on exposed sand for two surveys and 0.18 m and 0.24 m on submerged sand. Pan *et al.* (2015) have used high resolution airborne full waveform LiDAR to estimate shallow river bathymetry, and Höfle *et al.* (2009) used the characteristics of full waveform LiDAR to distinguish and map areas of water.

Terrestrial LiDAR systems (TLSs) are more restricted in their coverage but achieve greater accuracy (Smith and Vericat, 2014; Williams *et al.*, 2014), negate the need for high cost platforms such as aircraft, and can be used to retrieve data with a higher temporal frequency. Milan *et al.* (2007) have demonstrated the application of TLSs for morphological change detection in rivers, mapping rapid feature-scale change across a 6 km^2 area of the proglacial zone of Glacier du Ferpècle and Mont Miné, Switzerland. In addition, Brasington *et al.* (2012) achieved accurate morphologic unit and bed roughness mapping over a 1 km reach of the braided River Feshie, Scotland. Mobile platforms have been shown to increase the spatial range of TLSs in fluvial settings, with Alho *et al.* (2009), Lotsari *et al.* (2014) and Leyland *et al.* (2017) using boat-based survey, Vaaja *et al.* (2011) using cart-based survey, and Williams *et al.* (2013) using an amphibious all-terrain vehicle.

A number of studies have also been fusing techniques, with Leyland *et al.* (2017) integrating mobile laser scanning and multibeam echo sounding with acoustic Doppler current profiling to directly measure changes in river bank and bed, and Williams *et al.* (2013) and Lotsari *et al.* (2014) coupling high density acoustic doppler profiling with TLS to provide information on flow and sediment transport fields.

Terrestrial laser scanning has been used to characterize spatial patterns of grain size and roughness for bar surfaces (Heritage and Milan, 2009; Hodge *et al.*, 2009a, 2009b) and to characterize pebble clusters (Entwistle *et al.*, 2007), through the application of point cloud analysis algorithms. Milan *et al.* (2010) have used first return red-wavelength TLS to map instream habitat based upon water surface roughness characterization. Smith *et al.* (2012) have also demonstrated limited bathymetric capabilities of red-wavelength terrestrial laser scanning in calm shallow water. Terrestrial laser scanning has also been used to characterize riparian vegetation to assist in spatial roughness parameterization for 2D hydraulic modelling, which offers potential improvements to flood prediction (Antonarakis *et al.*, 2009, 2010; Manners *et al.*, 2013).

Green-wavelength, bathymetric LiDAR has been shown to be capable of whole system fluvial mapping, capturing both terrestrial and bathymetric surfaces as McKean *et al.* (2009) and Kinzel *et al.* (2013) have demonstrated using EAARL (the *experimental advanced airborne research LiDAR)* narrow-beam aquatic-terrestrial LiDAR. Bathymetric LiDAR has gained a strong presence in the literature around estuaries, with Valle *et al.* (2011) successfully modelling estuarine habitats using airborne bathymetric data. In fluvial systems bathymetric LiDAR however appear less effective for shallow water environments which are often the focus of geomorphic river investigations (e.g. gravel-bed rivers), with studies generally restricted to depths greater than 0.5 m (Allouis *et al.*, 2010; Bailly *et al.*, 2010; Milan and Heritage, 2012). Pan *et al.* (2015) suggest that full waveform LiDAR may offer improved shallow water bathymetry estimates.

Photogrammetry and structure-from-motion (SfM) methods

Terrestrial photogrammetry continues to be used in fluvial studies with sub-centimetre scale resolution (Lane, 2000). Errors on survey data are reported by Smith and Vericat (2015). Dietrich

(2010) has achieved mapping over 32 km of river using this technique. Bird *et al.* (2010) recognized the limited areal coverage achieved using conventional oblique photography extending their coverage through the use of a camera mounted on a long pole to map channel bed elevation linked to pool-riffle sequences.

Structure-from-motion (SfM) algorithms can automatically generate three-dimensional (3D) data from a set of photographs of the area interest. The algorithms retrieve the various camera positions and orientations used for a reconstruction. This technique coupled with the rapid development of image acquisition utilizing sUAVs allow rapid construction of accurate orthophotographs and DEMs from the images captured and has led to a recent significant increase in geomorphological research utilizing this combined approach (Table I). Westoby *et al.* (2012) highlight the effectiveness of SfM for geoscience applications essentially focusing on the low-cost, user-friendly photogrammetric technique for obtaining high-resolution datasets at a range of scales. Smith *et al.* (2016) note that many of the publications relating to SfM in physical geography are at present proof of concept studies, with many using the orthophotograph produced as part of the SfM process to detect features (e.g. Entwistle and Heritage, 2017).

Derivation of accurate DEMs, using photogrammetric methods, across fluvial environments has proved challenging due to their complexity and the variable presence of vegetation and water. Exposed surfaces have been successfully mapped by many researchers (e.g. Fonstad *et al.*, 2013; Smith and Vericat, 2014; Entwistle and Heritage, 2017), with the data becoming increasing used for subsequent, multi scale analysis (Smith and Vericat, 2014). Javernick *et al.* (2014) used SfM to carry out a detailed survey and subsequent error analysis of sub-meter resolution DEMs from two contiguous reaches of the braided Ahuriri River, New Zealand; mapping 3.3 km of watercourse in total. Imagery was acquired from high altitude (600–800 m from a helicopter), achieving mean vertical surface errors of ±0.1 m across non-vegetation areas.

Roughness metrics have also been derived from SfM photogrammetry; across large exposed (Leon *et al.*, 2015) and submerged areas (Entwistle and Heritage, 2017). Most recently Carbonneau and Dietrich (2017) have employed direct georeferencing techniques commonly used to position airborne LiDAR to generate ground elevation models with average mean residual errors of only ±0.06 m (equivalent to 1% of the flying altitude) utilising an sUAV with GPS position accuracy of 2.5 m. This success opens the way for DEM generation without the use of ground control points; further increasing the efficiency and ease of data collection using sUAV platforms. Woodget *et al.* (2015), Woodget and Austrums (2017), Dietrich (2017) and Entwistle and Heritage (2017) evaluate and expand on approaches to accurately survey bathymetric data using SfM.

Issues with data acquisition and processing have been reported, with a useful summary provided by Woodget *et al.* (2015). Sun glint issues are known to occur with remote sensing images (Legleiter, 2013) and UAV imagery (Visser *et al.*, 2015; Zeng *et al.*, 2017) and this may be reduced by flying when the sun is at its highest (Dietrich, 2017) and through glint removal algorithms (Overstreet and Legleiter, 2017).

Other remote sensing methods

Fausch *et al.* (2002) demonstrated the value of satellite remote sensing in characterizing the riverscape, whilst Gilvear and Bryant (2016) provide an excellent and up to date review of spaceborne remote sensing techniques. They conclude that remotely sensed data has wide application in detecting and mapping landforms, quantifying temporal change in fluvial landforms and elucidating on controlling processes. Bizzi *et al.* (2016) also review the advances in the use of remote sensed data to characterize fluvial hydromorphology concluding that such data could benefit the Water Framework Directive assessment process across Europe. Ecohydraulic information has also been derived from satellite survey of channel bathymetry and sedimentology and subsequent modelling using these data have facilitated fish habitat assessment at the river scale (Bergeron and Carbonneau, 2012). Of particular note is the increasing availability of Landsat data and Google Earth engine imagery which is now providing unprecedented information on land-surface changes. For example, Yousefi *et al.* (2016) succeeded in mapping and quantifying morphometric change over 20 meandering reaches of the Karoon River in Iran between 1989 and 2008.

Derivation of fluvial metrics and Point-cloud Modelling

Change detection and morphological characterization of fluvial systems is increasingly being dominated by the use of the DEM or digital terrain model (DTM) (Williams, 2012). Remote sensing methodologies (e.g. LiDAR and SfM) are used to collect point cloud data that can be imported into spatial analyses software, where the data can be interpolated to produce a modelled surface. A number of factors can introduce error into the DEM including survey point quality, sampling strategy, surface composition, topographic complexity and interpolation methods (Milan *et al.*, 2011). In fluvial geomorphology a common approach has been to re-survey rivers following events that may have changed the topography, such as large floods (Milan, 2012), and subtract the successive DEMs from one another to produce DEMs of Difference (DoDs) (Williams, 2012), that require error filtering for each of the DEMs involved. This approach has led to a step-change in our ability to understand spatial patterns of morphological response to forcing factors within fluvial systems (e.g. Pasternack and Wyrick, 2017). Some key developments have been made towards error assessment when using DEMs for fluvial studies in the last decade. Heritage *et al.* (2009) and Milan *et al.* (2011), have shown how error is spatially variable across a DEM, and often linked to local topographic variability (form roughness). These provide a workflow that allow 'Levels of Detection' to be applied to DEMs, that can be used to filter error in a spatially distributed manner. Heritage *et al.* (2009) also show the importance of considering survey strategy when collecting data, particularly when using more traditional field data retrieval approaches [total station and differential GPS (dGPS)]. A further widely used approach is that of Wheaton *et al.* (2010), who use fuzzy set theory coupled with a method for discriminating DoD uncertainty on the basis of the spatial coherence of erosion and deposition using Bayes Theorem. These workers suggest that various components of elevation uncertainty are collinear variables and do not exhibit a single monotic relationship to elevation uncertainty, and therefore apply a heuristic approach to the problem. More recent advances in point cloud analyses involve cloud-to-cloud comparisons rather than DEM differencing (Lague *et al.*, 2013), which has proved particularly useful in change detection analyses of vertical surfaces such as river banks (e.g. Leyland *et al.*, 2017).

Advances have also been made in the spatial interrogation of point cloud data at a range of scales. Cavalli *et al.* (2008) have also interrogated LiDAR DEMs to delineate channel types, through analysis of the residuals of elevations orthogonal to the regression line drawn along the channel profile, and the standard deviation of the local slope, and has proved particularly useful in delineation step-pool and riffle-pool reaches. The dense and highly accurate point clouds produced from terrestrial LiDAR have allowed detailed analysis at the grain-scale, including grain roughness and structure (Entwistle and Fuller, 2009; Heritage and Milan, 2009; Hodge *et al.*, 2009a, 2009b). Hodge *et al.* (2009a) analysed the distribution of surface elevations (1 mm spacing on small patches of gravel) and surface slope and aspect to provide information on grain packing and the role of grain size in determining surface structure, and grain orientation and imbrication. Heritage and Milan (2009) and Entwistle and Fuller (2009) found strong relationships between twice the standard deviation of the surface elevations in a small moving window over the point cloud, and grain size; most closely with the *c*-axis of gravel clasts, which are most closely associated with particle protrusion. These approaches are permitting full spatial description of the grain size and roughness of bar surfaces and have the potential to improve roughness characterization for hydraulic modelling (Milan, 2009), and potentially improve flood flow prediction.

Special Issue Advances

Demarchi *et al.* (2017) concentrate on the Piedmont region of the Italian Apennines, in particular the Po River. Remote sensing data (near red orthophotographs and LiDAR) was obtained for the entire region (25 000 km^2) of the land surface with a resolution of 0.4 m. The authors used a combination of very high resolution near infrared aerial imagery and low-resolution LiDAR to provide a hydromorphological characterization of rivers at a regional scale, offering an approach that may be used to answer basin-scale questions. Data were interrogated at the pixel-level, applying a 'fluvial corridor' toolbox (Roux *et al.*, 2015) to the detrended DTM, to delineate morphological features, and an object-based classification approach to identify and delineate 'riverscape' units from the near infrared imagery. The work allowed 1700 km^2 of floodplains to be mapped and delineated into geomorphological meaningful units, and allowed the production of a database (HyMo DB), where hierarchical clustering was used to classify river reaches from the database.

Sun glint (specular reflection of sun light from the water surface) can pose significant problems with regards to extracting river habitat metrics from remotely-sensed images of rivers, as sun glint often results in unusually bright pixels, and subsequent loss of data. Glint removal has been carried out in marine environments, however these techniques do not work well for shallow rivers. Overstreet and Legleiter (2017) detail the development, application and testing of a method for removing sun glint from shallow areas of the bed, from remotely sensed imagery. The technique overcomes over-correction (removal of too much reflectance) inherent in previous approaches, through accounting for non-neglible water-leaving near infrared radiance. The new approach develops a depth-assisted method for sun glint removal, requiring field measurements of depth and imagery that includes at least one near infrared band. Example data for the gravel-bed Snake River, showed improved r^2 values for depth prediction (from 0.66 to 0.76), when compared to previous approaches that fail to work well in shallow water environments such as gravel-bed rivers.

Pasternack and Wyrick (2017) provide a detailed assessment of topographic change along a 37 km reach of the coarse-grained, alluvial Lower Yuba River; a regulated river also influenced by mining, and an extreme flood over the period of the investigation (1999–2008). The study compared point cloud DEMs created using recent ground- and boat-based LiDAR, with earlier contour-based DEMs created using photogrammetry (0.6 m resolution). The morphological budget presented is for the full 37 km long reach, following the application of state-of-the-art error filtering (Wheaton *et al.*, 2010). The analysis of morphological change across multiple spatial scales provides useful insight into the morphodynamics of the river. In particular, the results that emerge from analysing how scour/fill varies along the river, and how morphological change volumes and mean vertical changes vary significantly for different morphological units, demonstrating how geomorphic change detection can be used to gain insight into morphological evolution. The longevity of remnant mining sediment was estimated based on a multi-scalar approach to quantifying geomorphic and associated volumetric change.

Marteau *et al.* (2017) use SfM photogrammetry to produce DEMs and assess geomorphic changes associated with a river restoration project in north west UK. The approach uses a low cost GoPro camera with a fish-eye lens attached to a drone. SfM photogrammetry is becoming a major technique in geomorphology in the capture of morphological change data, and for the first time this article demonstrates its' potential as a tool in monitoring channel response following river restoration; in this case an artificial channel created to restore the connection between two rivers. The authors use the SfM data to produce DEMs from a point cloud, and subtract these over a series of surveys to identify spatial patterns of scour and fill and report volumetric change, and carefully account for error. Although the use of fisheye lenses for photogrammetry has previously been criticized, the authors results are of high quality.

Thumser *et al.* (2017) introduce a new method for remotely sensing surface velocity in rivers in real time. The approach uses UAV-based particle tracking (RAPTR-UAV), using a combination of floating, infrared light-emitting particles and a programmable embedded colour vision sensor attached to a UAV to simultaneously detect and track the positions of objects. The approach can rapidly collect and process position data in real-time, and has the potential to improve hydraulic model validation, and increase understanding of process and form within river channels.

Wheaton *et al.* (2018) present a framework for the application of ecohydraulic fish habitat models at a range of scales, using salmon populations in the Columbia River basin (900+ sites in 12 watersheds) as an example. Readily available remotely-sensed data such as 10 m DEMs, geology and Landsat-derived vegetation layers, satellite and aerial imagery, coupled with reach-scale remotely-sensed data and at-a-site validation using more basic survey techniques (e.g. total stations), permit full geomorphic assessment and habitat modelling that transcends scale boundaries. The approach links habitat (defined by geomorphology, hydraulics, and water temperature dynamics), with population and life cycle modelling of the species in question. A conceptual and methodological toolbox is developed that operationalizes the notion that fish habitat should be studied at a landscape scale.

Conclusions

At the outset of this article we noted the value of remote sensing to generate data-sets rich in spatial information. The subsequent review of research has certainly shown this to be the case with sensors able to capture detailed datasets across often large areas allowing integrated analysis of form and process across a variety of spatial scales. Our investigation of the proliferation of remote sensing techniques in river research (Table I) clearly demonstrates the range of techniques being employed with particularly strong use of satellite-based data and more recently SfM derived data.

Marcus and Fonstad (2010) noted the drivers for remote sensing data collection were research needs, through investigation of new technologies and greater engagement of fluvial geomorphologists with spatial data. It would appear from the subsequent seven years that the development of new technologies is exerting the greatest influence; Smith and Vericat (2014) conclude that many studies published to date are proof of concept, concentrating on confirming the accuracy of the new remote sensing approaches rather than using the data more fully to generate initial new insights and ideas on geomorphic form and function. This is understandable but also disappointing. It is important to recognize the value of the data sets collected so far in the context of the error that they contain in relation to natural surface variability. Entwistle and Heritage (2017) note that part of the remotely sensed error in water depth is likely due to the inherent variability of the river bed being studied which is also not being picked up by the reference survey technique (for example their theodolite survey). A practical recognition of the impact of such error dependent on the character of the environment being studied is more important. This is in no way an excuse for poor surveying but it will allow researchers greater flexibility in analysing these early data sets and in developing increased geomorphic insight.

Marcus and Fonstad (2010) also concluded that the rise in remotely sensed fluvial research was serendipitous. Whilst this may be true to some degree, there appears to have been a genuine research driven desire to begin to exploit new remote sensed technologies with considerable research effort expended across many institutions and that individual desire appears to be continuing unabated assisted by the ability to utilize new remote sensed platforms cheaply and easily to obtain detailed and accurate spatial data. This is providing the individual researcher or small research grouping with tremendous opportunity to move the science of fluvial geomorphology forward unconstrained to a large degree of the need to secure substantial research funding. Fluvial geomorphologists have never before been in such a liberated position.

Many studies are also now developing sophisticated landscape models based on integrated survey techniques with the ability to work to common reference coordinates greatly aiding this process. In such a way the connectivity between terrestrial and aquatic zones is becoming increasingly understood (see for example Leyland *et al.*, 2017). The advent of newer and more sophisticated techniques in remote sensing should, however, not preclude the use of more traditional approaches, especially given the proliferation of data available for these techniques too. For instance, Lisle (2006) acknowledged the great value of the historic imagery availability from Google Earth allowing change mapping based on increasingly frequent images and other satellite-based sources such as Landsat data providing unprecedented temporal change information to investigate land surface changes.

It is exciting also to view the possibility of increasing use of remote sensed data to drive further studies with the DEMs with the reviews of Fausch *et al.* (2002) and Gilvear and Bryant (2016) amply demonstrating the proliferation of available data from multiple satellite platforms. Importantly these data are proving of great value in process modelling as Javernick *et al.* (2014) demonstrated using SfM derived DEMs to conduct 2D hydraulic modelling.

References

Abalharth M, Hassan MA, Klinkenberg B, Leung V, McCleary R. 2015. Using LiDAR to characterize logjams in lowland rivers. *Geomorphology* **246**: 531–541.

Abu-Aly TR, Pasternack GB, Wyrick JR, Barker R, Massa D, Johnson T. 2014. Effects of LiDAR-derived, spatially distributed vegetation roughness on two-dimensional hydraulics in a gravel-cobble river at flows of 0.2 to 20 times bankfull. *Geomorphology* **206**: 468–482.

Alho P, Kukko A, Hyyppä H, Kaartinen H, Hyyppä J, Jaakkola A. 2009. Application of boat-based laser scanning for river survey. *Earth Surface Processes and Landforms* **34**(13): 1831–1838.

Allouis T, Bailly JS, Pastol Y, Le Roux C. 2010. Comparison of LiDAR waveform processing methods for very shallow water bathymetry using Raman, near-infrared and green signals. *Earth Surface Processes and Landforms* **35**(6): 640–650.

Antonarakis AS, Richards KS, Brasington J. 2008. Object-based land cover classification using airborne LiDAR. *Remote Sensing of Environment* **112**(6): 2988–2998.

Antonarakis AS, Richards KS, Brasington J, Bithell M. 2009. Leafless roughness of complex tree morphology using terrestrial lidar. *Water Resources Research* **45**(10) W10401. https://doi.org/10.1029/2008WR007666.

Antonarakis AS, Richards KS, Brasington J, Muller E. 2010. Determining leaf area index and leafy tree roughness using terrestrial laser scanning. *Water Resources Research* **46**(6) W06510. https://doi.org/10.1029/2009WR008318.

Bailly JS, Le Coarer Y, Languille P, Stigermark CJ, Allouis T. 2010. Geostatistical estimations of bathymetric LiDAR errors on rivers. *Earth Surface Processes and Landforms* **35**(10): 1199–1210.

Belletti B, Rinaldi M, Buijse AD, Gurnell AM, Mosselman E. 2015. A review of assessment methods for river hydromorphology. *Environmental Earth Sciences* **73**(5): 2079–2100.

Bentley SG, England J, Heritage G, Reid H, Mould D, Bithell C. 2016. Long reach biotope mapping: deriving low flow hydraulic habitat from aerial imagery. *River Research and Applications* **32**(7): 1597–1608.

Bergeron N, Carbonneau PE. 2012. Geosalar: innovative remote sensing methods for spatially continuous mapping of fluvial habitat at riverscape scale. In *Fluvial Remote Sensing for Science and Management*, Carbonneau P, Piégay H (eds). John Wiley & Sons: Chichester; 193–213.

Bertoldi W, Gurnell AM, Drake NA. 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) W06525. https://doi.org/10.1029/2010WR010319.

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.

Biron PM, Choné G, Buffin-Bélanger T, Demers S, Olsen T. 2013. Improvement of streams hydro-geomorphological assessment using LiDAR DEMs. *Earth Surface Processes and Landforms* **38**(15): 1808–1821.

Bizzi S, Demarchi L, Grabowski RC, Weissteiner CJ, Van de Bund W. 2016. The use of remote sensing to characterise hydromorphological properties of European rivers. *Aquatic Sciences* **78**(1): 57–70.

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) W11519. https://doi.org/10.1029/2012WR012223.

Bywater-Reyes S, Segura C, Bladon KD. 2017. Geology and geomorphology control suspended sediment yield and modulate increases following timber harvest in temperate headwater streams. *Journal of Hydrology* **548**: 754–769.

Carbonneau P, Piégay H (eds). 2012. *Fluvial Remote Sensing for Science and Management*: John Wiley & Sons, Chichester.

Carbonneau PE, Dietrich JT. 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.

Carbonneau PE, Lane SN, Bergeron NE. 2004. Catchment-scale mapping of surface grain size in gravel bed rivers using airborne digital imagery. *Water Resources Research* **40**(7) W07202. https://doi.org/10.1029/2003WR002759.

Casado MR, Gonzalez RB, Kriechbaumer T, Veal A. 2015. Automated identification of river hydromorphological features using UAV high resolution aerial imagery. *Sensors* **15**(11): 27969–27989.

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.

Charlton ME, Large AR, Fuller IC. 2003. Application of airborne LiDAR in river environments: the River Coquet, Northumberland, UK. *Earth Surface Processes and Landforms* **28**(3): 299–306.

Crasto N, Hopkinson C, Forbes DL, Lesack L, Marsh P, Spooner I, Van Der Sanden JJ. 2015. A LiDAR-based decision-tree classification of open water surfaces in an Arctic delta. *Remote Sensing of Environment* **164**: 90–102.

De Rose RC, Basher LR. 2011. Measurement of river bank and cliff erosion from sequential LIDAR and historical aerial photography. *Geomorphology* **126**(1): 132–147.

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.

Dietrich JT. 2016. Riverscape mapping with helicopter-based structure-from-motion photogrammetry. *Geomorphology* **252**: 144–157.

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

Entwistle NS, Fuller IC. 2009. *Terrestrial Laser Scanning to Derive the Surface Grain Size Facies Character of Gravel Bars*, Laser Scanning for the Environmental Sciences. John Wiley & Sons: Chichester; 102–114.

Entwistle NS, Heritage GL. 2017. An evaluation DEM accuracy acquired using a small unmanned aerial vehicle across a riverine environment. *International Journal of New Technology and Research* **3**(7): 43–48.

Entwistle NS, Heritage GL, Johnson J, Hetherington D. 2007. Repeat terrestrial laser scanner survey of pebble cluster creation and formation in response to flow change. *Proceedings, Annual Conference*. Remote Sensing and Photogrammetry Society: Nottingham.

Fausch KD, Torgersen CE, Baxter CV, Li HW. 2002. Landscapes to riverscapes: bridging the gap between research and conservation of stream fishes: a continuous view of the river is needed to understand how processes interacting among scales set the context for stream fishes and their habitat. *AIBS Bulletin* **52**(6): 483–498.

Feyisa GL, Meilby H, Fensholt R, Proud SR. 2014. Automated water extraction index: a new technique for surface water mapping using Landsat imagery. *Remote Sensing of Environment* **140**: 23–35.

Fonstad MA, Dietrich JT, Courville BC, Jensen JL, Carbonneau PE. 2013. Topographic structure from motion: a new development in photogrammetric measurement. *Earth Surface Processes and Landforms* **38**(4): 421–430.

Gilvear D, Bryant R. 2003. Analysis of aerial photography and other remotely sensed data. In *Tools in Fluvial Geomorphology*, Kondolf GM, Piégay H (eds), second edn. John Wiley & Sons: Chichester chapter 6.

Gilvear D, Bryant R. 2016. Analysis of remotely sensed data for fluvial geomorphology and river science. In *Tools in Fluvial Geomorphology*, Kondolf GM, Piégay H (eds). John Wiley & Sons: Chichester chapter 6.

Glennie CL, Carter WE, Shrestha RL, Dietrich WE. 2013. Geodetic imaging with airborne LiDAR: the Earth's surface revealed. *Reports on Progress in Physics* **76**(8): 086801.

Gomez B, Mertes LA, Phillips JD, Magilligan FJ, James LA. 1995. Sediment characteristics of an extreme flood: 1993 upper Mississippi River valley. *Geology* **23**(11): 963–966.

Hardy TB, Anderson PC, Neale MU, Stevens DK. 1994. Application of multispectral videography for the delineation of riverine depths and mesoscale hydraulic features. In *Effects of human-induced changes on hydrologic systems*. Symposium of the American Water Resources Association: Jackson Hole, Wyoming; 445–454.

Heritage G, Fuller I, Charlton M, Brewer P, Passmore D. 1998. CDW photogrammetry of low relief fluvial features: accuracy and implications for reach scale sediment budgeting. *Earth Surface Processes and Landforms* **23**(13): 1219–1233.

Heritage G, Large A (eds). 2009. *Laser Scanning for the Environmental Sciences*. John Wiley & Sons: Chichester.

Heritage GL, Milan DJ. 2009. Terrestrial laser scanning of grain roughness in a gravel-bed river. *Geomorphology* **113**(1): 4–11.

Heritage GL, Milan DJ, Large AR, Fuller IC. 2009. Influence of survey strategy and interpolation model on DEM quality. *Geomorphology* **112**(3): 334–344.

Hicks DM, Duncan MJ, Walsh JM, Westaway RM, Lane SN, Jonas DL. 2000. The braided Waimakariri River: new views of form and process from high-density topographic surveys and time-lapse imagery. In *Gravel Bed Rivers V*, Mosley MP (ed). The New Zealand Hydrological Society: Wellington.

Hodge R, Brasington J, Richards K. 2009a. Analysing laser-scanned digital terrain models of gravel bed surfaces: linking morphology to sediment transport processes and hydraulics. *Sedimentology* **56**(7): 2024–2043.

Hodge R, Brasington J, Richards K. 2009b. In situ characterization of grain scale fluvial morphology using terrestrial laser scanning. *Earth Surface Processes and Landforms* **34**(7): 954–968.

Höfle B, Vetter M, Pfeifer N, Mandlburger G, Stötter J. 2009. Water surface mapping from airborne laser scanning using signal intensity and elevation data. *Earth Surface Processes and Landforms* **34**(12): 1635–1649.

Hohenthal J, Alho P, Hyyppä J, Hyyppä H. 2011. Laser scanning applications in fluvial studies. *Progress in Physical Geography* **35**(6): 782–809.

Hooke JM. 1984. Changes in river meanders: a review of techniques and results of analyses. *Progress in Physical Geography* **8**(4): 473–508.

Javernick L, Brasington J, Caruso B. 2014. Modeling the topography of shallow braided rivers using Structure-from-Motion photogrammetry. *Geomorphology* **213**: 166–182.

Kinzel PJ, Legleiter CJ, Nelson JM. 2013. Mapping river bathymetry with a small footprint green LiDAR: applications and challenges. *JAWRA Journal of the American Water Resources Association* **49**(1): 183–204.

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**(7): 838–842.

LaChapelle E. 1962. Assessing glacier mass budgets by reconnaissance aerial photography. *Journal of Glaciology* **4**(33): 290–297.

Lague D, Brodu N, Leroux J. 2013. Accurate 3D comparison of complex topography with terrestrial laser scanner: application to the Rangitikei canyon (NZ). *ISPRS Journal of Photogrammetry and Remote Sensing* **82**: 10–26.

Lane SN. 2000. The measurement of river channel morphology using digital photogrammetry. *The Photogrammetric Record* **16**(96): 937–961.

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 SN, Richards KS, Chandler JH. 1994. Developments in monitoring and terrain modelling of small-scale riverbed topography. *Earth Surface Processes and Landforms* **19**: 349–368.

Legleiter CJ. 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. 2013. Mapping river depth from publicly available aerial images. *River Research and Applications* **29**(6): 760–780.

Leon JX, Roelfsema CM, Saunders MI, Phinn SR. 2015. Measuring coral reef terrain roughness using 'Structure-from-Motion' close-range photogrammetry. *Geomorphology* **242**: 21–22.

Lewin J, Manton MMM. 1975. Welsh floodplain studies: the nature of floodplain geometry. *Journal of Hydrology* **25**(1-2): 37–50.

Leyland J, Hackney CR, Darby SE, Parsons DR, Best JL, Nicholas AP, Aalto R, Lague D. 2017. Extreme flood driven fluvial bank erosion and sediment loads: direct process measurements using integrated Mobile Laser Scanning (MLS) and hydro acoustic techniques. *Earth Surface Processes and Landforms* **42**(2): 334–346.

Lisle RJ. 2006. Google Earth: a new geological resource. *Geology today* **22**(1): 29–32.

Lotsari E, Vaaja M, Flener C, Kaartinen H, Kukko A, Kasvi E, Hyyppä H, Hyyppä J, Alho P. 2014. Annual bank and point bar morphodynamics of a meandering river determined by high-accuracy multitemporal laser scanning and flow data. *Water Resources Research* **50**(7): 5532–5559.

Malinowski R, Höfle B, Koenig K, Groom G, Schwanghart W, Heckrath G. 2016. Local-scale flood mapping on vegetated floodplains from radiometrically calibrated airborne LiDAR data. *ISPRS Journal of Photogrammetry and Remote Sensing* **119**: 267–279.

Manners R, Schmidt J, Wheaton JM. 2013. Multiscalar model for the determination of spatially explicit riparian vegetation roughness. *Journal of Geophysical Research: Earth Surface* **118**(1): 65–83.

Marcus WA, Fonstad MA. 2010. Remote sensing of rivers: the emergence of a subdiscipline in the river sciences. *Earth Surface Processes and Landforms* **35**(15): 1867–1872.

Marteau B, Vericat D, Gibbins C, Batalla RJ, Green DR. 2017. Application of structure from motion photogrammetry to river restoration. *Earth Surface Processes and Landforms* **42**(3): 503–515.

McKean J, Nagel D, Tonina D, Bailey P, Wright CW, Bohn C, Nayegandhi A. 2009. Remote sensing of channels and riparian zones with a narrow-beam aquatic-terrestrial LIDAR. *Remote Sensing* **1**(4): 1065–1096.

Mertes LA, Smith MO, Adams JB. 1993. Estimating suspended sediment concentrations in surface waters of the Amazon River wetlands from Landsat images. *Remote Sensing of Environment* **43**(3): 281–301.

Milan DJ. 2009. Terrestrial laser scan-derived topographic and roughness data for hydraulic modelling of gravel-bed rivers. In *Laser Scanning for the Environment Sciences*, Heritage GL, Large ARG (eds). Wiley-Blackwell: Oxford; 133–146.

Milan DJ. 2012. Geomorphic impact and system recovery following an extreme flood in an upland stream: Thinhope Burn, northern England, UK. *Geomorphology* **138**(1): 319–328.

Milan DJ, Heritage GL. 2012. LiDAR and ADCP use in gravel bed rivers: advances since GBR6. In *Gravel-bed Rivers: Processes, Tools, Environments*, Church M, Biron P, Roy A (eds). John Wiley & Sons: Chichester; 286–302.

Milan DJ, Heritage GL, 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 DJ, Heritage GL, Large AR, Fuller IC. 2011. Filtering spatial error from DEMs: implications for morphological change estimation. *Geomorphology* **125**(1): 160–171.

Milan DJ, Heritage GL, Large ARG, Entwistle NS. 2010. Mapping hydraulic biotopes using terrestrial laser scan data of water surface properties. *Earth Surface Processes and Landforms* **35**(8): 918–931.

Milan DJ, Heritage GL, Tooth S, Entwistle NS. 2018. Morphodynamics of bedrock-influenced dryland rivers during extreme floods: Insights from the Kruger National Park, South Africa. Geological Society of America Bulletin, in press.

Nelson A, Dubé K. 2016. Channel response to an extreme flood and sediment pulse in a mixed bedrock and gravel-bed river. *Earth Surface Processes and Landforms* **41**(2): 178–195.

Overstreet BT, Legleiter CJ. 2017. Removing sun glint from optical remote sensing images of shallow rivers. *Earth Surface Processes and Landforms* **42**(2): 318–333.

Pan Z, Glennie C, Hartzell P, Fernandez-Diaz JC, Legleiter C, Overstreet B. 2015. Performance assessment of high resolution airborne full waveform LiDAR for shallow river bathymetry. *Remote Sensing* **7**(5): 5133–5159.

Pasternack GB, Wyrick JR. 2017. Flood-driven topographic changes in a gravel-cobble river over segment, reach, and morphological unit scales. *Earth Surface Processes and Landforms* **42**(3): 487–502.

Pierdicca N, Pulvirenti L, Chini M, Guerriero L, Candela L. 2013. Observing floods from space: Experience gained from COSMO-SkyMed observations. *Acta Astronautica* **84**: 122–133.

Roux C, Alber A, Bertrand M, Vaudor L, Piégay H. 2015. “FluvialCorridor”: a new ArcGIS toolbox package for multiscale riverscape exploration. *Geomorphology* **242**: 29–37.

Salo J, Kalliola R, Häkkinen I, Mäkinen Y, Niemelä P, Puhakka M, Coley PD. 1986. River dynamics and the diversity of Amazon lowland forest. *Nature* **322**: 254–258.

Schofield LA, Danson FM, Entwistle NS, Gaulton R, Hancock S. 2016. Radiometric calibration of a dual-wavelength terrestrial laser scanner using neural networks. *Remote Sensing Letters* **7**(4): 299–308.

Silva TS, Costa MP, Melack JM, Novo EM. 2008. Remote sensing of aquatic vegetation: theory and applications. *Environmental Monitoring and Assessment* **140**(1): 131–145.

Smith M, Vericat D, Gibbins C. 2012. Through-water terrestrial laser scanning of gravel beds at the patch scale. *Earth Surface Processes and Landforms* **37**(4): 411–421.

Smith MW, Carrivick JL, Quincey DJ. 2016. Structure from motion photogrammetry in physical geography. *Progress in Physical Geography* **40**(2): 247–275.

Smith MW, Vericat D. 2014. Evaluating shallow-water bathymetry from through-water terrestrial laser scanning under a range of hydraulic and physical water quality conditions. *River Research and Applications* **30**(7): 905–924.

Smith MW, Vericat D. 2015. From experimental plots to experimental landscapes: topography, erosion and deposition in sub-humid badlands from structure-from-motion photogrammetry. *Earth Surface Processes and Landforms* **40**(12): 656–1671.

Straatsma MW, Baptist MJ. 2008. Floodplain roughness parameterization using airborne laser scanning and spectral remote sensing. *Remote Sensing of Environment* **112**(3): 1062–1080.

Tarolli P. 2014. High-resolution topography for understanding Earth surface processes: opportunities and challenges. *Geomorphology* **216**: 295–312.

Thompson C, Croke J. 2013. Geomorphic effects, flood power, and channel competence of a catastrophic flood in confined and unconfined reaches of the upper Lockyer valley, southeast Queensland, Australia. *Geomorphology* **197**: 156–169.

Thompson CJ, Croke J, Fryirs K, Grove JR. 2016. A channel evolution model for subtropical macrochannel systems. *Catena* **139**: 199–213.

Thumser P, Haas C, Tuhtan JA, Fuentes-Pérez JF, Toming G. 2017. RAPTOR-UAV: real-time particle tracking in rivers using an unmanned aerial vehicle. *Earth Surface Processes and Landforms* **42**: 2439–2446. https://doi.org/10.1002/esp.4199.

Vaaja M, Hyyppä J, Kukko A, Kaartinen H, Hyyppä H, Alho P. 2011. Mapping topography changes and elevation accuracies using a mobile laser scanner. *Remote Sensing* **3**(3): 587–600.

Valle M, Borja Á, Chust G, Galparsoro I, Garmendia JM. 2011. Modelling suitable estuarine habitats for Zostera noltii, using ecological niche factor analysis and bathymetric LiDAR. *Estuarine, Coastal and Shelf Science* **94**(2): 144–154.

Visser F, Buis K, Verschoren V, Meire P. 2015. Depth estimation of submerged aquatic vegetation in clear water streams using low-altitude optical remote sensing. *Sensors* **15**(10): 25287–25312.

Warburton J, Davies TRH, Mandl MG. 1993. A meso-scale field investigation of channel change and floodplain characteristics in an upland braided gravel-bed river, New Zealand. *Geological Society, London, Special Publications* **75**(1): 241–255.

Westaway RM, Lane SN, Hicks DM. 2000. The development of an automated correction procedure for digital photogrammetry for the study of wide, shallow, gravel-bed rivers. *Earth Surface Processes and Landforms* **25**(2): 209–226.

Westoby MJ, Brasington J, Glasser NF, Hambrey MJ, Reynolds JM. 2012. ‘Structure-from-Motion’ photogrammetry: a low-cost, effective tool for geoscience applications. *Geomorphology* **179**: 300–314.

Wheaton JM, Brasington J, Darby SE, Sear DA. 2010. Accounting for uncertainty in DEMs from repeat topographic surveys: improved sediment budgets. *Earth Surface Processes and Landforms* **35**(2): 136–156.

Wheaton JM, Bouwes N, Mchugh P, Saunders C, Bangen S, Bailey P, Nahorniak M, Wall E, Jordan C. 2018. Upscaling site-scale ecohydraulic models to inform salmonid population-level life cycle modeling and restoration actions -Lessons from the Columbia River Basin. *Earth Surface Processes and Landforms* **43**(1): 21–44.

Williams DR, Romeril PM, Mitchell RJ. 1979. Riverbank erosion and recession in the Ottawa area. *Canadian Geotechnical Journal* **16**(4): 641–650.

Williams R. 2012. DEMs of difference. In *Geomorphological Techniques*, Clarke L (ed) . British Society for Geomorphology: London.British Society for Geomorphology 2(3.2)

Williams RD, Brasington J, Hicks M, Measures R, Rennie CD, Vericat D. 2013. Hydraulic validation of two-dimensional simulations of braided river flow with spatially continuous aDcp data. *Water Resources Research* **49**(9): 5183–5205.

Williams RD, Brasington J, Vericat D, Hicks DM. 2014. Hyperscale terrain modelling of braided rivers: fusing mobile terrestrial laser scanning and optical bathymetric mapping. *Earth Surface Processes and Landforms* **39**(2): 167–183.

Winterbottom SJ, Gilvear DJ. 1997. Quantification of channel bed morphology in gravel-bed rivers using airborne multispectral imagery and aerial photography. *River Research and Applications* **13**(6): 489–499.

Woodget AS, Austrums R. 2017. Subaerial gravel size measurement using topographic data derived from a UAV-SfM approach. *Earth Surface Processes and Landforms* **42**: 1434–1443. https://doi.org/10.1002/esp.4139.

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**(1): 47–64.

Woodget AS, Fyffe C, Carbonneau PE. 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**(4): 857–870. https://doi.org/10.1002/esp.4285.

Wright A, Marcus WA, Aspinall R. 2000. Evaluation of multispectral, fine scale digital imagery as a tool for mapping stream morphology. *Geomorphology* **33**(1): 107–120.

Wulder MA, White JC, Nelson RF, Næsset E, Ørka HO, Coops NC, Hilker T, Bater CW, Gobakken T. 2012. Lidar sampling for large-area forest characterization: a review. *Remote Sensing of Environment* **121**: 196–209.

Yousefi S, Pourghasemi HR, Hooke J, Navratil O, Kidová A. 2016. Changes in morphometric meander parameters identified on the Karoon River, Iran, using remote sensing data. *Geomorphology* **271**: 55–64.

Zeng C, Richardson M, King DJ. 2017. The impacts of environmental variables on water reflectance measured using a lightweight unmanned aerial vehicle (UAV)-based spectrometer system. *ISPRS Journal of Photogrammetry and Remote Sensing* **130**: 217–230.

