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Fluvial and aquatic applications of Structure from Motion photogrammetry and UAV/drone technology

Overview

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Abstract

Structure from motion (SfM) has seen rapid uptake recently in the fluvial and aquatic sciences. This uptake is not least due to the widespread availability of cheap UAVs/drones, which help mitigate the challenging terrain and deliver efficient and reproducible and high-accuracy images and topographical data. These data can have unprecedented spatio-temporal coverage and includes measurements of fluvial and aquatic topography, hydraulics, geomorphology and habitat quality. SfM data also offer novel quantification of underwater archaeology, structures and aquatic organisms. Studies are shifting from proof-of-concepts in topographic survey to genuine applications including grain size mapping, bathymetric surveys, geomorphological mapping, vegetation mapping, restoration monitoring, habitat classification, geomorphological change detection and sediment transport path delineation. Integrating point cloud analyses and orthophoto mosaics with digital elevation models (DEMs) has been shown to be effective in providing novel process understanding of fluvial and aquatic systems. Underwater and through-water studies are beginning to overcome problems of accessibility, visibility and image distortion. Archival photographs and video (both above- and underwater) are being reprocessed using a SfM workflow to generate three-dimensional surfaces and objects from historical surveys, thereby extending the time period over which change can be detected. Recently, a SfM workflow has been developed to model free water surfaces with clear potential for future exploitation in hydraulics, sediment transport and river bed evolution studies. Future applications of SfM could seek to exploit the daily repeat coverage of high-resolution satellite images but must be mindful of the necessary investment in this development versus the increasing availability and coverage of spaceborne LiDAR.

Graphical/Visual Abstract and Caption

SfM is facilitating novel process understanding of fluvial and aquatic topography, hydraulics, geomorphology and habitat quality and, as well as providing novel data on underwater archaeology, structures and organisms.

INTRODUCTION

Structure-from-Motion (SfM) with multi-view stereo (MVS), hereafter together referred to as SfM, is a topographic survey technique that has emerged from advances in computer vision and traditional photogrammetry. It can produce high-quality dense three-dimensional point clouds [BOX 1] of an object or surface for minimal financial cost. While SfM has only been applied to geosciences applications relatively recently, in that short time it has had a transformative effect on the discipline[1], providing exceptionally cost-efficient and fast 3D surveying at spatial extents, spatial densities and with point accuracies comparable to other survey methods (Table 1). There is also a very pragmatic reason for the rapid uptake of SfM photogrammetry; it enables Unmanned Aerial Vehicle (UAV)/drone data to be used more readily and consumer-grade UAVs have evolved greatly in the last decade in electronic sophistication, ease-of-use and reduced cost. Thus UAV image data has made SfM photogrammetry appealing in comparison with traditional photogrammetry; for instance, Laliberte et al (2010)[2] had to develop a complex photogrammetric procedure to orthorectify imagery from a drone survey. In comparison to acquiring airborne Light Detection and Ranging (LiDAR) data, acquiring images for SfM is several orders of magnitude cheaper.

	Without SfM	**With SfM**
Spatial extent (km^2)	TS, dGPS : < 1.0 TLS: < 5.0 AP: < 50 ALS, MBES: < 100	Ground-based platform: 0.01 to 1.0 Airborne platform: < 5.0
Spatial density (pts./m^2)	TS, dGPS: < 5.0 AP: < 10 ALS, MBES: < 10 TLS: < 10,000	1 to 10,000
Point acquisition rate (pts./hr)	TS: 10^2 dGPS: 10^3 AP, MBES: 10^4 ALS, TLS: 10^6	millions
Point accuracy (m)	TS: < 0.001 dGPS: < 0.005 TLS, MBES: < 0.05 ALS: < 0.2 AP: < 0.5	0.01 to 0.2

Table 1. Typical properties of major survey approaches. TS: total station, dGPS: differential global positioning system (or GNSS), TLS: terrestrial laser scanner, AP: aerial stereo-photogrammetry, ALS: airborne laser scanner, MBES: Multi Beam Echo Sounder. Adapted from Table 2.3 in Carrivick et al. (2016). Note that with SfM spatial density and point accuracy especially are dependent on image resolution (pixel size), surface texture and lighting and distance of camera from surface of interest.

Early research utilising SfM in the geosciences represented the first phase of 'proof-of-concept' studies (e.g. Refs. 1,3-6) where demonstration high resolution data sets were coupled with validation against more established methods, usually laser scanning. Over time, these research efforts have resulted in clear guidance on best-practice workflows for both field data collection and post-processing and the development of new, rigorous methods for assessments of precision, accuracy and uncertainty (Refs. 3, 7-9).

In the two related geoscience disciplines of fluvial and aquatic sciences SfM has been embraced, but not holistically and with different applications. There is great potential for each to learn from the other's applications and specifically from their survey methods, problems and emerging solutions.

A range of image acquisition platforms from ground-based, to UAVs/drones, microlights and helicopters, means that the scope of many of these fluvial and aquatic sciences studies is very variable. The focus of this previous SfM-related work has been to obtain relatively standard data products (i.e. gridded digital elevation/surface/terrain models, DEM/DSM/DTMs) that were previously only possible using more expensive survey methods including airborne LiDAR and Terrestrial Laser Scanning (TLS).

Yet, Structure-from-Motion can provide much more than just a DEM as a fully 3D colour point cloud is initially generated from which orthophoto mosaics can be extracted. BOX 1 summarises the range of data products SfM methods offer. A most recent branch of SfM work in the geosciences has considered both the extraction of meaningful information beyond standard topographic data products (e.g. change detection, grain size analysis and facies mapping, automated organism identification) and the development of new methods for expanding the potential applicability of SfM in fluvial and aquatic environments, e.g. bathymetry mapping, decadal-scale studies through the SfM processing of historical imagery. Aquatic applications have seen a particular focus on such methodological developments as SfM must overcome problems of visibility and accessibility of underwater terrain.

The aim of this review is to provide a synthesis of this most recent phase of SfM usage in both fluvial aquatic applications. We include examples from river, beach, intertidal and shallow marine settings but exclude coastal cliffs because these studies are more aligned to mass movement geomorphology than to fluvial or aquatic sciences and are almost unaffected in the SfM workflow by working in/around water. We evaluate the success of SfM in expanding our survey capabilities and using this new capacity to address real world applications, providing new insights into process-based knowledge.

LATEST DEVELOPMENTS IN FLUVIAL APPLICATIONS

Usage of SfM in the fluvial sciences is classified and described here by generic application, comprising: (1) topographic mapping/survey; (2) change detection and impact assessment; (3) grain size analysis; and (4) modelling of the water surface for hydraulic applications (Figure 1).

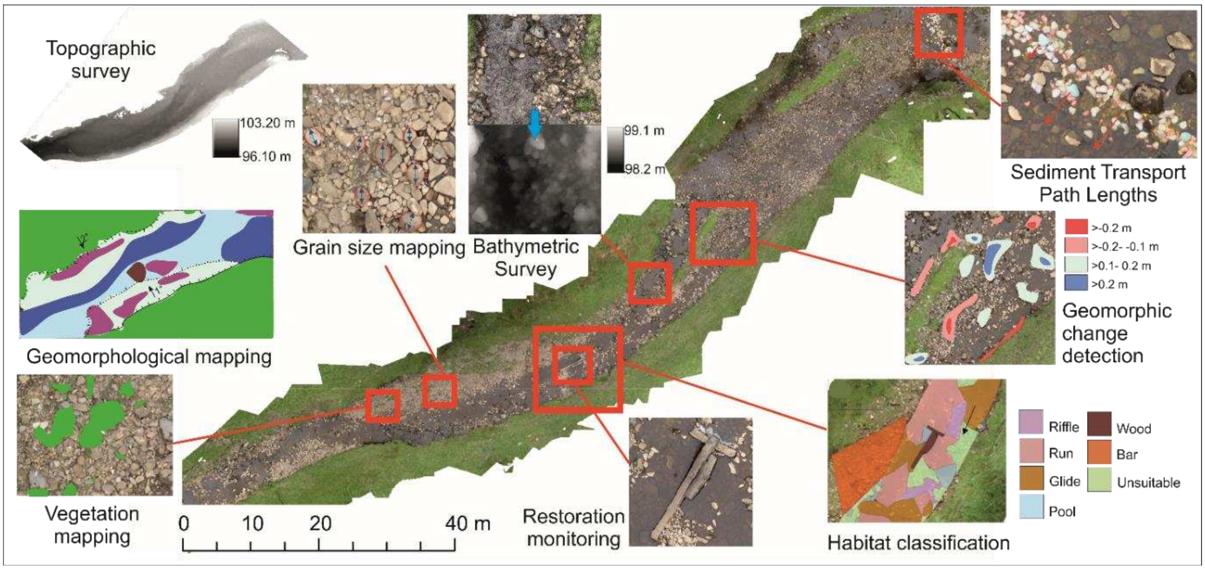


Figure 1. Summary of typical SfM applications in fluvial systems.

Topographic mapping/Survey

Survey and mapping of fluvial corridors using aerial or satellite imagery has a long history and has until the last few decades depended on classic analogue and digital photogrammetry for three-dimensional measurement. The methods for this three-dimensional survey and mapping have been supplemented with airborne Light Detection and Ranging (LiDAR) and most recently by SfM. The main scientific benefit of the adoption of SfM by fluvial scientists was perceived as the bridging of spatial scales between detailed analysis across small areas and coarser broad scale satellite-based measurements. However, at least as important has been the pragmatic driver for the uptake of SfM methods; SfM is a very a low-cost remote sensing approach enabled by the co-evolution of consumer-grade UAV/drone technology. Early adopters of SfM in geomorphology typically focused on fluvial environments (e.g. Ref. 5) and since then fluvial surveys have been the focus of SfM testing and validation studies (e.g. Refs. 11, 12).

Whilst cameras can be handheld or ground-based, it has been UAV-platforms that are most commonplace, resulting in a survey area of typically several hundred metres in length. At intermediate (tens to hundreds of metres) spatial scales, SfM can represent the inherent complexity and heterogeneity of real riverscapes and challenge classic conceptual models that aggregate over these complexities to present smooth downstream trends[13]. Processing of SfM datasets is not limited by the SfM method, nor by the camera platform but by computing power, which with modern computers and GPU processing, for example, is becoming much less of a limitation than with early geoscience usage of SfM. Large scale process work is not proceeding very fast due to the scale limitations of UAV/drone operations. Thus studies that are using SfM methods to cover larger spatial scales are doing so by using helicopter-based imagery across kilometres (Ref. 10) and even tens of kilometres (32-35 km[13, 14]).

Mapping applications of SfM fall into three categories: (i) topographic survey, potentially to drive a numerical model or as part of change detection; (ii) manual aerial mapping and feature identification; (iii) supervised image classification for semi-automated fluvial surveys. It should be noted, however, that individual studies combine several of these categories[15].

The most obvious limitation of SfM applied as a fluvial topographic survey method is the difficulty of direct acquisition of submerged topography, as the stream bed is not always visible. Nonetheless, Woodget et al. (2015)[16] identified that through-water bathymetric survey is possible under clear water conditions. Subsequently, Dietrich (2017)[17] presented a more sophisticated multi-camera refraction correction algorithm to obtain bathymetry in depths up to 2 m. The generation of orthophoto mosaics offers further potential when coupled with optical bathymetric mapping methods in shallow and clear water conditions. However, in sunny conditions, consideration of the original image aspect is necessary because sun glint can result in a different empirical depth function for different aspects[11]. In practice, there can be little difference between refraction-correction methods and empirical depth function methods of bathymetry extraction from SfM[18].

The combination of digital surface models and orthophoto mosaics represents a powerful tool for fluvial scientists. SfM-derived topography can be used for numerical modelling of river flows, while the orthophoto mosaic can assist with model validation[19,20]. The topographic detail and fully three-dimensional perspective afforded by the range of viewpoints, as opposed to that from airborne LiDAR, which is essentially downward-looking, is advantageous especially when evaluating river floods in urban environments[21,22]. A SfM workflow can also support post flood analysis with 2D numerical modelling applied to SfM-derived topography and compared against high water marks observed in imagery[12,23].Manual interrogation and digitization of both SfM-derived orthophoto mosaics and Digital Surface Models (DSMs) has been used to evidence a wide range of fluvial features, including geomorphological and river corridor maps[24], surface flow types[25], geomorphological and ecosystem impacts of a Eurasian beaver reintroduction program[26], large woody debris accumulations[18], and the spatial distribution, thickness and volume of river ice[27].

Through adaptation of established methods, recent studies have demonstrated the potential for automated identification of features using SfM-derived orthophoto mosaics, topographic data, or both. For example, Casado et al. (2015)[28] used a supervised Artificial Neural Network (ANN) classification to automatically detect hydromorphological features including substrate features, water features (i.e. riffles, glides, pools and shallow water) and vegetation features with 81 % accuracy. Prosdocimi et al. (2015)[29] classified SfM-surveyed river banks from the topographic signature alone, using a roughness index to identify areas of bank erosion. Merging these two approaches, Langhammer and Vacková (2018)[30] performed a supervised classification of a multi-band dataset combining both the orthophoto mosaic and topographic variables to discriminate key fluvial facies such as fresh versus old sand and gravel accumulations for rapid mapping of geomorphological responses to floods.

Despite the diversity of SfM data products having clear applications in the study of fluvial ecology when coupled into a unified riverscape data source, the potential of SfM photogrammetry for quantifying physical habitat complexity and heterogeneity and thereby evaluating drivers of ecological diversity has yet to be fully realised. Tamminga et al. (2015)[18] demonstrated an early example of this by running a 2D hydraulic model on SfM-derived topography and bathymetry whilst generating a metric of fish habitat suitability based on both modelled water depths and velocities, overhead vegetation cover mapped from orthophoto mosaics and grain size estimates using image texture methods. Similarly, Marteau et al. (2017)[31] compiled an assortment of SfM-derived data, including multiple point clouds, DEMs, facies maps and channel roughness maps, to evaluate erosion and deposition within a river restoration scheme; yet, such integrated activity is not yet commonplace.

Change detection and impact assessment

The speed and efficiency of the SfM workflow (in terms of both time and money) lends it to re-survey and thus to differencing of repeated DEMs or DSMs to estimate: topographic change, volumetric sediment budgets via the morphological method, and physical habitat conditions both pre- and post-disturbance. The latter are critical for assessing physical impacts and measures are often demanded by local policies and international legislation concerned with environmental impacts and river restoration. SfM offers to mitigate the data scarcity associated with such pre- and post-disturbance monitoring by: (i) being applicable to archival/historical imagery; (ii) depending on the camera platform, which is usually a UAV, offering relatively quick and easy and thus cheap re-survey capability without compromising spatial density or coverage nor precision and accuracy; and (iii) offering a suite of data products from just a single workflow.

SfM has been used to quantify the extent, magnitude and form of topographic change in fluvial environments over a variety of scales, from bank erosion at individual cross sections[32], individual river restoration schemes[31], gorge sections over several hundred metres[33], to 1 km braided reaches[17] and reaches over tens of kilometres in length[14]. The workflow could easily be applied to any other related fluvial or aquatic application such as natural flood management[34], or to other aspects of catchment management and river engineering. The level of resolvable topographic change depends on several factors, including image quality, image network geometry, ground control, surface texture and the camera platform (height)[35] and is thus variable between these studies. Whilst cameras can handheld, mounted on poles, or tethered to kites or blimps they are most typically attached to or fully integrated within UAVs[36]. Typically, UAV-based surveys are sufficiently accurate to enable elevation changes of ~0.2-0.3 m to be detected reliably[32,33]. Vegetation presents a challenge for accurate differencing and is a limitation that is particularly inherent within aerial-based surveys.

The need for high quality ground control has been traditionally considered to be paramount to avoid structural errors in topographic models[7] from yielding erroneous sediment budgets. However, given that UAVs now produce geotagged imagery many users and readers of this paper will be tempted to use SfM in a direct georeferencing workflow. The key of the direct georeferencing method is the ability of SfM to reconstruct the 3D geometry of an image network and thus to produce an accurate scale for an image. Direct georeferencing offers the potential to capture more control measurements (albeit displaced above the survey volume) but current consumer-grade technology is limited by positional accuracy which impacts the resulting point precision [8]. Nonetheless, the pace of technological improvement is encouraging and it is likely that direct georeferencing will become standard practice in the future. Moreover, there are situations such as upon unstable slopes or during flood events where direct georeferencing could be required for safety. Certainly, depending on the required threshold level of detection, a direct georeferencing workflow is suitable for change detection [37, 38]. Rapid and affordable SfM surveys open up the possibility of so-called 4D fluvial surveys, where regular multi-temporal surveys enable fluvial dynamics to be quantified at the event-scale. From a practical standpoint, this presents an opportunity for near real-time evaluation of natural disasters, as demonstrated recently by Izumida et al. (2017)[39]. Following a flood event, a breached levee in the city of Joso, Japan, resulted in a crevasse splay, two fatalities and evacuation of 6000 residents.

Comparison of pre- and post-event 3D surveys enabled quantification of the area of destruction including volumetric estimates of erosion and subsequent deposition of extensive lobe shaped sand mounds.

From a more academic standpoint, the increased availability of repeat surveys at the event-scale permits a clearer understanding of process-form linkages in fluvial systems as maps of topographic change can be interrogated to better understand the processes responsible for the change: so-called 'mechanistic segregation' [40,41]. Kasprak et al. (2015)[42] clearly demonstrated this potential in a flume study where mechanistic segregation of SfM maps of topographic change were coupled with tracer path length measurements using SfM orthophoto mosaics. This rich dataset enabled confirmation of the hypothesis of Hundley and Ashmore (2009)[43] that the distance between confluence-diffluence couplets provides a first-order approximation of sediment travel distances in braided systems as channel bar heads and margins are important deposition sites. Whilst there is much work to be done in translating such clear advances in process understanding into real-world fluvial systems, these early studies clearly demonstrate the potential of SfM data products to revolutionise our process understanding of natural riverscapes and beyond.

The timescales required for fluvial adjustment mean that several important processes cannot be studied using contemporary datasets alone as records must span several decades before clear identification of process drivers can be established (e.g. direct human impacts or human-induced climate changes). Addressing this timescale problem, SfM-based methods have permitted sources of data from archival imagery of fluvial systems to be 'unlocked'[44]. For example, Bakker et al. (2018)[45] were able to quantify the morphology and topographic changes of an Alpine stream between 1959 and 2005 using an archival SfM method, and they evaluated the effects of both flow abstractions and climate-driven glacial retreat on sediment transport rates. Incorporation of timescales to SfM analyses requires that efforts must be made to consider and mitigate structural errors in resulting topographic models[46]. Methods for dealing with survey errors probabilistically to yield appropriate minimum levels of detection were developed previously for other high resolution topographic datasets[47]and have been readily transferred to SfM datasets. In particular, James et al. (2017b)[9] present a point cloud [BOX 1] differencing method adapted from the M3C2 method[48] that incorporates spatially variable precision arising from photo-based surveys.

Grain size

With SfM methods yielding such high resolution data, opportunities for data interrogation to extract information beyond topographic mapping have recently developed. For fluvial scientists, grain-size information is a clear priority area as reflected in the recent proliferation of focused efforts to extract this from SfM data[18,20,449-57]. This focussed effort is not surprising because information on river bed material size is required for the majority of fluvial investigations, including the prediction of boundary shear stress and sediment transport rates, to parameterise hydraulic and morphodynamic models, to evaluate the sustainability and effectiveness of critical infrastructure (i.e. bridges and flood protection works), to inform river restoration activities and to assess the quality and diversity of fluvial mesohabitats for both fish and macroinvertebrates. Yet, despite the near-ubiquitous requirement for grain-size data, current standard manual field data collection methods are time-consuming, destructive and necessarily limited by the financial cost of time and personel[58].

Whilst the adoption of SfM in fluvial environments has not yet led to any fundamentally new approaches in digital gravelometry, it has nevertheless increased the accessibility and achievable spatial scale of existing approaches. In a particular example of this increased accessibility, the improvements in UAVs/drones within a SfM workflow can be used to deliver a fully robotic grain size mapping method that does not rely on ground control[56]. In general, three main approaches to using SfM to map grain size exist:

(1) **'Photo-sieving' methods**: direct mapping of individual surface grains from high resolution, close range overhead photographs using one of several software packages (e.g. Sedimetrics[58]; BASEGRAIN[59]). The generation of scaled georeferenced orthophoto mosaics as part of the SfM workflow lends itself to subsequent application of these techniques, particularly from low altitude surveys (e.g. Ref. 20).

(2) **Grain-size proxies from images**: developing an empirical relationship between surface grain size and image properties such as semi-variograms of image texture (e.g. Refs. 60, 61) or the spectral or frequency content of images (e.g. Refs. 62-64). Again, these were developed for use with centimetre-resolution aerial (for image texture approaches) or close-range (for spectral approaches) imagery but have since been applied and adapted for use on SfM-derived orthophoto mosaics (e.g. Refs. 18, 53, 55).

(3) **Grain-size proxies from topography**: developing an empirical relationship between surface grain size and a measure of the surface roughness of 3D point clouds or 2D rasters derived from high resolution topographic data products. Roughness-based approaches were first applied to data from Terrestrial Laser Scanners (TLS) (e.g. Refs. 65-705) but owing to the ease of data acquisition especially over larger areas, most recent studies have applied the roughness proxy method to dense point clouds arising from the SfM workflow (e.g. Refs. 50-55, 71).

These three approaches are all limited in that only subaerially-exposed grains can be measured; the refraction correction of Dietrich (2017)[17] cannot be applied to the orthophoto mosaic and the increased surface noise (reported by Woodget et al., 2015[16]) renders even the roughness-based approach problematic. Vegetated areas also present problems for each of the SfM-based grain size estimation methods.

Comparison of the three methods shows clear differences in their performance. Woodget and Austrums (2017)[53] report that the grain-size estimates from the roughness-based approach are more than an order of magnitude more accurate that those from the image texture approach. The sensitivity of the texture approach to image blurring (reported by de Haas et al., 2014[72]) and potential inteference caused by shadows[18] are thought to explain this poor performance. Yet, in further work, Woodget et al. (2018)[55] demonstrated that improved performance (reduced blurring) was possible through use of a gimbel for image stabilization. More significantly, they demonstrated that the texture-grain-size relationship is compromised by the adjustment of image brightness as part of the orthophoto mosaic generation process and so they developed a novel workflow to apply the texture approach to single images instead of the SfM-derived orthophoto mosaic. Camera lens properties were extracted from SfM software to approximately locate each image relative to the orthophoto mosaic and constrain the subsequent application of an algorithm to identify and match points visible in both the single image and the orthophoto mosaic and then georeference that image. This novel workflow bypasses the issue of variable pixel scales that would be pronounced in low-altitude imagery and was shown by Woodget et al. (2018)[55] to outperform the roughness approach.

Consistent and reproducible SfM-based grain-size estimations have yet to be achieved. The reasons for this inconsistency are firstly that there is an absence of a standardised SfM survey protocol and the variability introduced throughout the workflow by choices of camera[54], camera platform, survey range, number of images, processing settings, etc.[1].

Second, field collection of grain-size data used for calibration and validation is inconsistent and can have a large effect on results as a result of sampling bias. Wolman counts[52], line-by-number[54], grid-by-number[55], areal sampling[51] and the results of close-range photo-sieving[23,71] have each been used recently to provide grain-size data for comparison with SfM-estimates. Different grain size percentiles and axis measurements have also been used for comparison[51,52]. Nonetheless, ground validation; methods that consistently measure surface particles at a scale similar to that of the images used for SfM, can enable derivation of a grain size mapping algorithm that represents a good measured-modelled correlation.

Third, the sedimentology and topography of the field site itself will influence the performance of each of the methods. Perhaps the key limiting factor is that the effect of imbrication on the expression of grain size as roughness is complex and poorly understood. Pearson et al. (2017)[51] systematically evaluated the performance of the roughness approach on a variety of sedimentary facies and showed good performance over a range of gravel sizes and shapes and even on imbricated gravels while demonstrating that very different relationships emerge for each facies type, thereby emphasising the need for calibration data. However, the method performed poorly on poorly-sorted sediment patches, which explains the similarly poor performance observed by Westoby et al. (2015)[23] on Antarctic moraines. Thus, it seems that the majority of fluvial environments offer an opportunity for application of SfM-based gravelometry owing to the well-observed sorting effect of fluvial transport. Certainly, Pearson et al. (2017)[51] showed a strong performance of the roughness-approach on a moderately well sorted patch at close range. The extent to which this can be upscaled remains to be explored fully. Furthermore, distinguishing between underlying topographic variation (or 'form-roughness') and grain-scale variability is also challenging and requires careful choice of detrending method. The single-image texture method of Woodget et al. (2018)[55] will be limited where steep slopes are observed unless an image can be acquired that remains perpendicular to the slope face.

Perhaps the most robust way forward with SfM-based grain size estimates lies in a combination of existing methods. The two image-based methods attempt to measure the planar dimensions of the grains, while all current roughness-based approaches focus only on vertical topographic variability, though calculation of a greater variety of roughness measurements could at least in part address this limitation[73]. Comparison of estimates from each automated method might be expected to help identify potentially unreliable data points or to allow automated identification of a sediment facies type and subsequent choice of the most appropriate method. However, such comparisons are easier said than done and it would seem that a dominant share of the variability is found in either image texture or roughness so perhaps a solution lies in a check method that would allow a decision (texture or roughness) to be made given the bed properties.

Water surface structure and hydraulics

A water surface can be regarded as either diffuse-like (quasi-Lambertian), mirror-like (specular reflection) or as transparent (refraction)[74] and different measurement methods aim to exploit one of these properties. However, exploitation of one of these surface properties requires mitigating issues due to the other two. For example, Wang et al. (2018)[75] have recently presented a two-stage method for dealing with specular reflection in UAV imagery; they firstly detect regions of images affected by specular reflection using an intensity ratio and secondly they restore those regions based on local cell/pixel information.

Recent investigations have highlighted the potential use of SfM for reconstructing free water surface both instantaneously and at very high spatial resolution (in a flume)[74,76]. Nonetheless, mobile clear water surfaces represent a serious technical challenge to image matching algorithms. Ferreira et al. (2017)[76] overcame these issues, achieving (DSLR) camera synchronisation by adapting an external electronically-controlled triggering box and artificially 'seeding' the water with 1 mm cork particles to provide a visible surface texture. Point precision for the water surface was ~1 mm while accuracy was determined to be 1.1 mm by simulating the water surface through an array of targets placed on a plane close to the expected water surface. Reliability was assessed visually via 3D visualisation to detect outliers from the expected (water) surface of interest. Alternatively, Rupnik et al. (2015)[74] used three oblique (DSLR) HD video cameras at a 10 m baseline aligned manually with a laser dot visible in all frames from all cameras and a combination of dust particles and retro-reflective floating water surface targets.

It is clear that an improved ability to reconstruct water surfaces in high spatial and temporal resolution opens up new research possibilities. For example, examining hydraulics around a single stem vegetation, Ferreira et al. (2017)[76] evidenced a wake with non-normally distributed wave crest heights, which is a wave character that has previously been associated with steep ocean waves (e.g. Ref. 77) but is still physically unexplained in terms of its connection to vegetation and probably requires creation of new theories in fluvial hydraulics.

APPLICATIONS IN AQUATIC SCIENCES

Usage of SfM in aquatic sciences can also be classified by generic application, including: (1) mapping shallow marine topography, (2) substrate structure and habitat complexity; (3) underwater archaeology and structural engineering assessments; (4) identification of organisms (Figure 2).

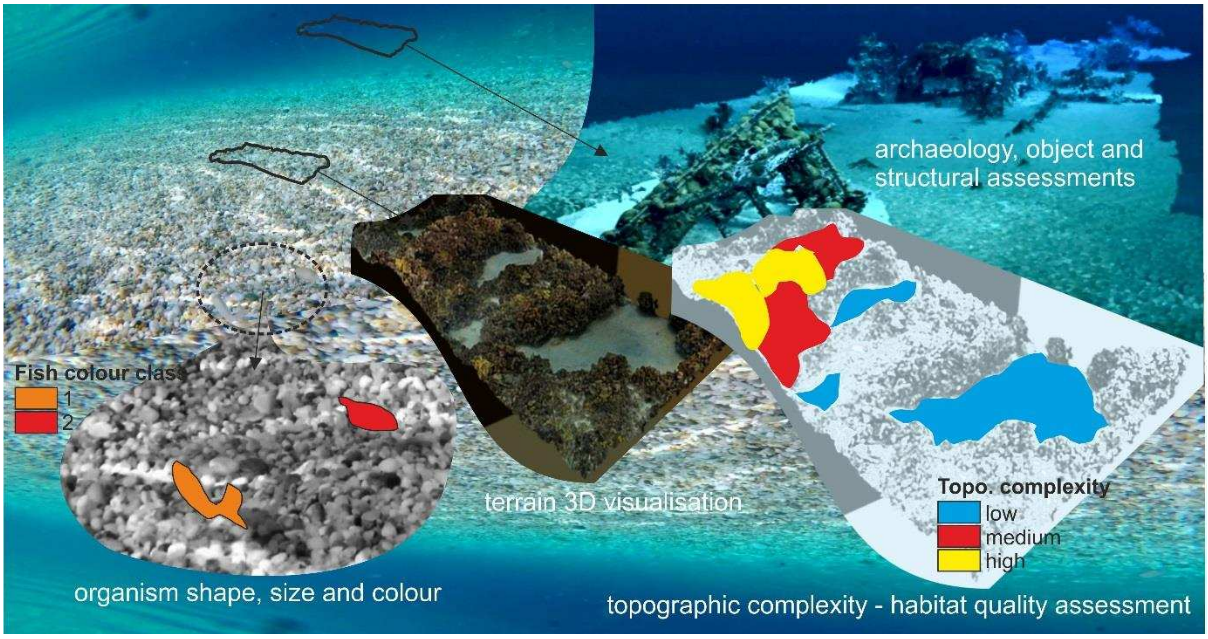


Figure 2. Summary of typical SfM applications in aquatic systems.

Inter-tidal topography

Efficient topographical and geomorphological surveys of inter-tidal topography and beaches require tools that combine high accuracy, high spatial density and good quality reproducibility. For those reasons, as well as speed and low cost, SfM has been applied to the problem of acquiring shallow marine topography in coastal, estuarine, mudflat and intertidal zones where access is difficult and ground conditions frequently changing. In these settings both ground-based (e.g. Ref. 78) and airborne platforms including microlights (e.g. Ref. 79) as well as the more common UAVs/drones[80, 81] to be used to acquire images. Other shallow marine settings are reviewed in the next section because they are not conducive to UAV/drone platform usage and must overcome a different set of problems; through water and underwater imaging.

In these settings sub-optimal survey conditions persist due to flight plan constraints, GPS measurement errors, sub- optimal distribution of GCPs and complex terrain that is often wet with residual tidal water. Nonetheless, 0.02 to 0.05 m 3D position precision has been shown to be obtainable [73-81]. With that precision and repeated high resolution (0.05 m) surveys low textural contrast and sun glint problems can be mitigated to reveal hitherto un-quantifiable inter-tidal morphodynamics of mudflats, sand beaches and gravel beaches, via orthophotographs and differenced DEMs[73, 75, 76]. The problem of the time required to deploy, survey and collect GCPs versus the time available between successive tides as reported by Jaud et al. (2016)[75] appears to have been mitigated by a direct georeferencing approach (see change detection section) by Jaud et al. (2018)[82]. Besides employing SfM, Jaud et al. (2018)[82] also excitingly report proof-of-concept results from a lightweight hyperspectral system which they mounted upon a UAV.

Overall, Inter-tidal applications of SfM have improved: the delineation of coastlines, coastal zone delineation, and most especially small (high resolution) spatio-temporal changes in surface characteristics and morphology. The latter has greatly improved the detection of coastal litter, ecological habitat dynamics and beach process-form understanding, and the quantification of sediment budgets.

Shallow marine sea bed structure and habitat complexity

Usage of SfM for bed structure and habitat complexity has focussed on shallow marine settings, but the problems, methods and solutions are immediately transferable to other aquatic settings such as lacustrine environments, and slow-flowing fluvial reaches, for example. Different physical structures within a small spatial area allow for more microhabitat types, greater niche space, and can increase biological diversity[83]. Furthermore, for a given spatial scale certain distinct 'keystone structures' may be particularly crucial in providing resources necessary to support a large number of species[84]. Traditional downward-looking approaches to mapping, especially within deeper water using ship-board swath bathymetry which is usually obtained via multibeam echosounders (MBES), tend to smooth topography and fail to image under overhanging cliffs (e.g. Ref. 85). Contrastingly, SfM can be applied with oblique- and side-looking images and can thus produce rugged 3D topography including (within) cavities and hollows.

Some (green wavelength and also multi-spectral fluorescence) laser scanners have been deployed through-water to characterise shallow marine topographic/bathymetric/habitat structural complexity over the last decade or so (e.g. Refs. 86-89), in a similar manner to that achieved for fluvial river substrates (e.g. Refs. 25, 90). However, these shallow marine studies have been limited in number and coverage due to the financial cost of the equipment and due to the logistical problems of deploying the equipment in that environment. In contrast, SfM is proving uniquely capable of characterising the complexity of shallow marine topography, especially coral reefs, in high spatial detail, focussed 'patch-scale' and wide 'colony-scale' (e.g. Ref. 91) spatial coverage, and with precision and accuracy comparable to that obtained with laser scanners, yet with minimal hardware and at minimal cost. The ability of SfM-derived data to span scales is important for habitat analyses because individuals of different species and with different body sizes and morphologies influence structural complexity at different scales and that complexity is key to ecosystem functioning[84].

In a proof of concept type study for monitoring changes and identifying biological activity on coral reefs, Casella et al. (2017)[92] employed *through-water* photography (Figure 3) from a camera mounted on a drone during early morning (low-angle light) and with an undisturbed water due to negligible wind conditions. They obtained both an orthorectified aerial photomosaic and a bathymetric digital elevation model (DEM). In comparison with airborne LiDAR data they verified that the orthorectified aerial photomosaic was accurate to ~1.4 m and that the bathymetric difference between their SfM-derived DEM and the LiDAR dataset was -0.016 ± 0.45 m (1σ). These accuracies should be a useful guide for studies seeking to realise SfM opportunities in aquatic studies and specifically through-water applications.

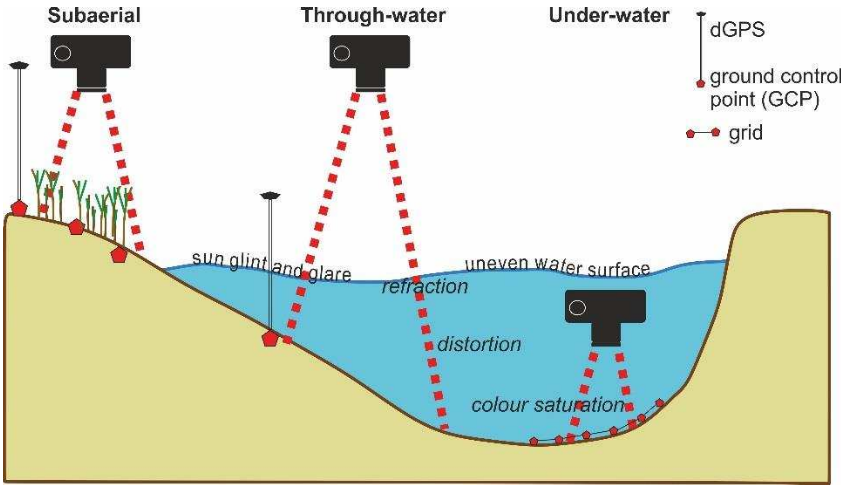


Figure 3. Comparison of the set up of SfM applications in fluvial and aquatic sciences highlighting some of the major access, positioning and image degradation problems that they must overcome.

Underwater SfM techniques (Figure 3) avoid imaging issues associated with a water surface, but encounter lighting and definition; saturation, problems. Underwater SfM techniques have primarily been utilized for seafloor habitat characterization, bathymetry mapping, marine environment inspections and archaeological surveys. In particular coral reefs have received relatively intense scrutiny for their vulnerability to environmental change and due to their relative visibility as they are often located within a clear and shallow water environment. Furthermore, coral reef surface complexity (3D/2D surface area), slope, and curvature are important predictors of organism abundance, biomass and diversity, and they also affect benthic current velocities associated with the food particle supply for suspension feeding corals. Many SfM studies have employed a diver swimming along underwater grids (e.g. Refs 93-96), where those grids consist of lines, markers, or other guides to aid judgment of coverage, density and distance of image acquisition. Grids partly mitigate the problems of determining precise 3D position underwater where satellite positioning and radio communications are inhibited (Figure 3).

In contrast, Storlazzi et al. (2016)[97] used previously collected, uncalibrated underwater monocular video, and Ferrari et al. (2016)[98] employed an autonomous underwater vehicle (AUV) equipped with multiple cameras. The latter acquisition enabled precise trajectory control and thus permitted repeated surveying of spatially precise observational patches. In these coral reef studies surface 'rugosity' has been the generally preferred metric of structural complexity, defined as the ratio between 3D surface area and 2D planar area. Although this metric is calculated with ArcGIS path distance tool[83] it is apparently confused in definition with subaerial examples of 'tortuosity'. It does not consider roughness in multiple directions although Ferrari et al. (2016)[98] calculated the ratio of surface area to planar area and reported this as rugosity. Other measures such as the fractal dimension should be considered to accommodate large (> 10^2 m^2) spatial coverage (e.g. Ref. 95). Rugosity was traditionally measured underwater using a chain and tape[99] whereas with 3D digital data it is commonly calculated using standard tools in ArcMap's benthic terrain modeller extension[100].

AUV video was also used for SfM by Robert et al. (2017)[9101] to examine vertical and overhanging submarine habitats. Their study is exceptional for being conducted partially at 1500 m depth. It is an example of the big datasets being incorporated to SfM studies because it included 2500 frames and nearly 3 hrs of Remotely operated vehicle (ROV) video footage, requiring ~ 10 hrs of computing time and a 12 Gb dataset. They produced generalised additive linear models to determine which derived terrain variables were most useful in explaining observed spatial patterns in abundance, number of species and diversity. Robert et al. (2017)[101] comment that whilst MBES-derived metrics were most useful in explaining ecological spatial patterns, SfM-derived metrics were particularly useful for the description of very fine-scale habitat selection as spatial resolutions of < 0.01 m were achieved. Furthermore, distinctions between dead coral framework and live coral patches were facilitated in SfM reconstructions, due to colour preservation and particularly due to an ability to place highly-detailed textures over meshes.

Underwater archaeology and structural engineering assessments

Shipwrecks and other underwater archaeological structures must usually be recorded underwater *in situ* in a time-consuming and expert-judgment reliant manner. In an approach to mitigate these documentations, Mertes et al. (2014)[102] used a diver-propelled rig with six 50-watt video lights, a dive computer for depth, a level, and a viewfinder that gave the diver feedback. They swam 10, 25-min surveys with a constant height above the wrecks Hetty Taylor and a schooner Home, which both lie at the bottom of Lake Michigan at 32 and 53 m of water, respectively. After finding an optimal scaling, translation and rotation to fit their 3D model to their hand survey they found that the longer the baseline of measurement, the higher the percentage of error between hand-measured lengths and lengths taken from the model. A full exploration of the accuracy of SfM applied to archive images[103] concluded that SfM offered considerable utility as a 3D vision technology as an information rich and relatively affordable underwater archaeological survey method. However, they cautioned that SfM was examined only as a post-processing analytical tool and if it were to be used as a stand-alone recording technique then centimetre-scale precision would be inadequate for small sites with a lot of internal structural details. Some examples of SfM-derived models of shipwrecks and other underwater structures are freely available to view on Sketchfab, such as the SS Thistlegorm Wreck by Simon Brown: https://sketchfab.com/models/d4e49cce7d53470b8afead0b94313817

O'Byrne et al. (2016)[104] also concluded that SfM was prone to failing when applied to reconstructing precise structural surfaces and objects for engineering structural integrity inspections. These inspections of 3D shape of offshore infrastructural elements are of great practical importance when analysing forces exerted by waves, winds and currents but are very expensive and difficult to perform. O'Byrne et al. (2016)[104] found that paired-camera stereo photogrammetry was reliable for 3D representations of structural micro-form, and especially of colonisation by marine growth species which tend to be overlooked in design considerations, but they noted that both SfM and stereo photogrammetry methods were dependent on surface texture, lighting and camera settings and thus could perform differently in other similar settings.

Organisms

Biomass and respiration rates in all aquatic organisms, chlorophyll concentration in photosynthetic organisms, and clearance and pumping rates of marine sponges and tunicates are all affected by organism surface area and volume[105]. Common methods for measuring surface area and volume of marine organisms include water displacement and paraffin dipping and require removal of the subject from its natural environment (e.g. see citations within Ref. 106). In the case of marine benthic animals such as corals and sponges this relocation typically results in death of the organism, thus preventing continuous observations over time. Therefore Lavy et al. (2015)[106] employed SfM to determine surface area and volume of corals and marine sponges. In comparison to the commonly-employed methods, they found that SfM accuracy of simple geometry models was found to be unaffected by the size of the modelled object within the tested range of < 6500 cm^3. However, object shape and posture had a major effect on the accuracy of the model; massive and flat corals were reconstructed well, whereas branching corals were reconstructed poorly. Using SfM, House et al. (2018)[107] have suggested that there are relationships between 2D and 3D metrics of (different types of) coral that can be used for empirically converting between the two.

Measurements of organism shape are also important for understanding organism behaviour. Fish body shapes are commonly observed from AUV platforms for behavioural analyses but since these fish are moving, rotating and changing shape they require very special development of SfM methods to accommodate that non-rigid state. Che et al. (2016)[108] have proposed a non-rigid SfM workflow that combines a particle filter to focus on fish trajectory tracking, an algorithm to locate salient feature points, extraction and correspondence of key feature points, an expectation maximization model to realize non-rigid 3D shape reconstruction, and a linear dynamical system for improving reconstruction in severe cases of noise and missing data.

NOVEL DEVELOPMENTS

Through-water and underwater fluvial and aquatic applications of SfM are more challenging than more commonplace subaerial surveys as they must overcome access problems, geolocation problems and target surface visibility problems (Figure 3). It is the third of these problems that has been the subject of most novel technical developments in SfM.

Geolocation is awkward underwater because satellite signals and radio waves are rapidly absorbed by water. A solution to these problems has been proposed by Huang and Kaess (2016)[109] and is termed by them as acoustic structure from motion (ASFM). ASFM uses multiple, general sonar viewpoints of the same scene to reconstruct the 3D structure of select point features while minimizing the effects of accumulating error. ASFM provides several advantages over other simultaneous localisation and mapping (SLAM) methods for AUV data; unlike previous approaches no planar assumptions about the environment are required, and ASFM is more accurate than pairwise approaches because it uses constraints from more than two images to eliminate drift and recover 3D landmark positions. Unfortunately ASFM is presently restricted in speed and utility due to a lack of automatic feature extraction; what kind of sonar image features are most stable and useful remains an open problem.

Target surface visibility problems can include attenuation of colour intensity and brightness, occlusion, shape distortion, sun glint and glare, and shadow (Figure 3). These problems can in part be mitigated by image acquisition strategies but inevitably also give recourse to novel image processing. For example, Xu et al. (2016)[110] developed some guided image filtering and Bryson et al. (2016)[111] have developed true colour correction of autonomous underwater vehicle imagery, each to mitigate water column induced colour/frequency-dependent attenuation and backscatter. Starek and Giessel

(2017)[112] have presented a denoising method for point cloud analysis to filter SfM-derived substrate points prior to implementation of a method of band ratio optimization, or optical bathymetric inversion, designed to mitigate occlusion effects in a shallow (~ 0.3 m) littoral coastal beach setting. Novel image processing recently designed explicitly for removing sun glint effects from remotely sensed imagery of shallow parts of beds has been presented by Overstreet and Legleiter (2018)[113]. Their technique requires field measurements of (shallow) water depth and it requires images that include at least one NIR band and overcomes a fault of previous approaches; namely removal of too much reflectance, by including out-going near infra-red radiance.

For deeper water, a novel method referred to as 'fluid lensing' requires sophisticated hardware and computing but is looking promising for correcting through-water wave-distorted images for subsequent SfM processing. Chirayath and Earle (2016)[114] described fluid lensing as using water-transmitted wavelengths to passively image underwater objects at high-resolution by exploiting time-varying optical lensing events caused by surface waves. They showed how fluid lensing as a passive system is presently limited by signal-to-noise ratio and water column optical properties to ~10 m depth over visible wavelengths in clear waters. They achieved < 0.1 m-scale resolution bathymetry through-water and across a 15 km^2 area[106]. Bryson et al. (2016)[111] anticipate that (reconstructed) true colour images of a seabed will be useful for distinguishing between coral species and other benthic organisms and have been shown to be related to chlorophyll pigment composition and benthic organism health, for example.

BOX 1

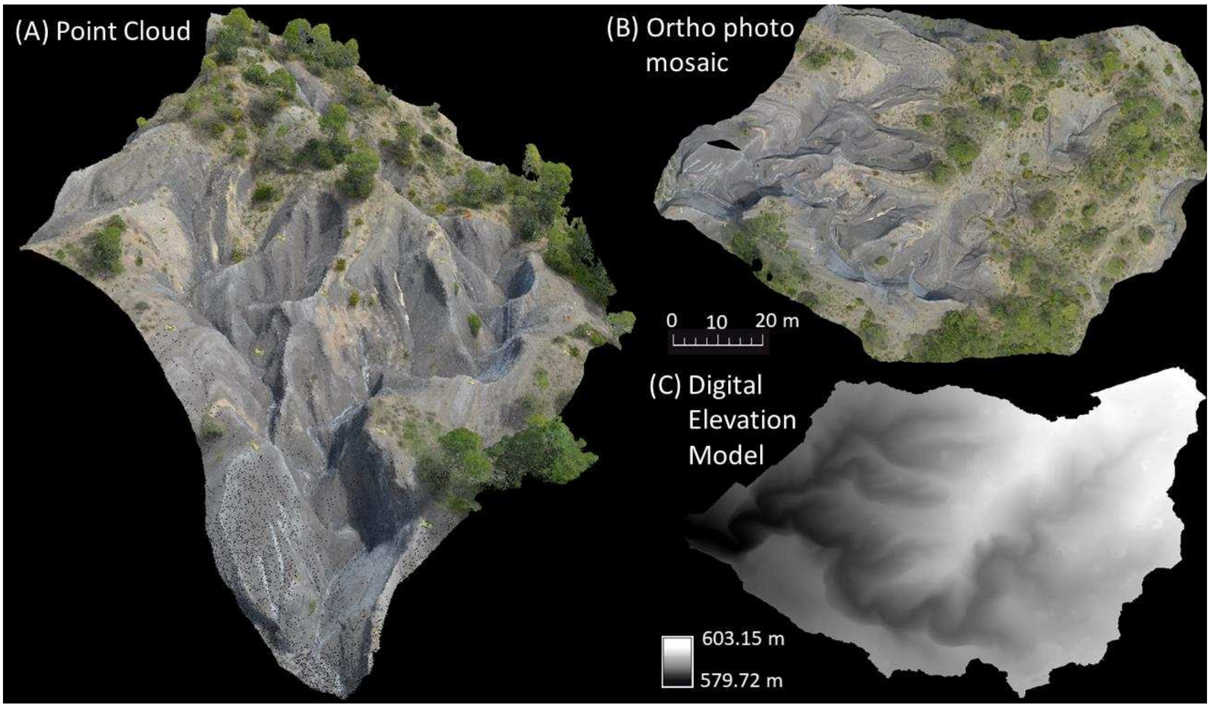
DATA PRODUCTS FROM SfM

SfM can be used to produce an orthophoto mosaic and a point cloud. An orthophoto mosiac (Figure B) is a georectified (and often geo-located) geometrically-accurate merge or stitch of overlapping images with distortions due to camera lens, perspective and topography removed and projected planimetrically. Orthophoto mosaics have utility as a backdrop for displaying other data upon, for measuring true distances between identifiable points and for interrogating colour-based characteristics spatially. They can used with image analysis techniques for feature identification/mapping and as a basis for change detection.

A point cloud (Figure A) is a set of data points in three-dimensional space. Each point has *X*,*Y*,*Z* coordinates and some additional attributes, such as RGB colour information and the intensity of signal return, for example. The points are irregularly sampled, spatially incomplete (e.g., submerged parts of river channels: see our discussion on this), and include 3D elements such as vegetation and vertical features such as river banks or cliffs.

In the geosciences, point clouds are most commonly produced by remote sensing, that is surveying whilst not directly in contact with the point or surface of interest. Equipment typically used to acquire 3D point clouds are airborne LiDAR (Light Detection and Ranging) scanners (ALS) or terrestrial LiDAR scanners (TLS) for subaerial applications, or swath bathymetry systems, usually Multi Beam Echo Sounders (MBES) for submarine environments. ALS, TLS and MBES are all very expensive systems and none of them produces orthophotographs. Thus SfM is attractive to geoscientists for not only being cheap but also for producing additional useful data as well as a point cloud. Furthermore, ALS and TLS can only be applied subaerially, MBES can only be applied subaqueously and both sets of equipment require different expertise. Another advantage of a SfM workflow over the other point cloud generating systems is that SfM data processing is very much the same irrespective of the scale (coverage and density) or of the environment.

Interpolating a raw point cloud onto a 2D gridded digital elevation model (DEM) (Figure C) generally results in a reduction in spatial resolution and thus accuracy. Therefore it is desirable to study fluvial and aquatic topography and processes directly with point clouds to preserve the resolution and accuracy of the original data, to better handle the evaluation of uncertainty associated to topographic change measurements and to be more suitable to study vegetation characteristics and steep features of the landscape. Developing tools to perform such direct point-cloud analysis represents the focus of much recent research.



Box 1 figure 1: Structure-from-Motion generated 3D true-colour point cloud (A), orthophoto mosaic (B) and DEM (C).

Gridding a point cloud is a data-reduction process. Since point clouds are not homogenous in point density gridding can serve most simply to create a uniform density of data. A summary of all points falling within a single DEM grid cell can also be extracted; such sub-grid statistics are often used in roughness analyses. Gridding might involve interpolation if no point cloud data are within a single cell area and thus must be estimated by surrounding data points.

In the fluvial and aquatic sciences, point clouds are primarily used to create interpolated 3D surfaces such as digital elevation models (DEMs) or Triangulated Irregular Networks (TINS) of natural terrain, organisms and of man-made objects. These raster grid processing methods are commonplace because they are enabled easily within Geographical Information System (GIS) software and thus benefit from a large library of fast algorithms dedicated to geometrical analysis, drainage network computation and topographic change measurement. Raster grid surfaces also facilitate measurement of distances, area and volumes, visualization and animation, for example.

Conclusions and future developments

In conclusion, fluvial and aquatic applications of SfM are rapidly developing in number and quality. They are progressing from proof-of-concept type studies to delivering process-understanding. The most promising and exciting scientific developments have come where studies collect and interrogate data using SfM that would otherwise be unobtainable. For example, spatial heterogeneity has been deconstructed and analysed whilst the ability to rapidly re-survey has produced event-scale change detection and sediment budgeting which can be used both to identify drivers of change and compared to morphodynamic model results of river bed evolution. Decadal timescale changes to fluvial topography and aquatic habitat structure have been quantified by re-processing of archived/historical images and video. Robust characterisation and quantification of a free water surface pattern using SfM is very exciting and has many usages including facilitation of future estimations of bedform properties. Specifically, a clear distinction can be made between (i) advances that are due to the intrinsic characteristics of the SfM processing workflow, and (ii) advances that are linked to the characteristics of the platforms that acquire the images used in SfM processing (Table 2). These advances are enabling (i) fully 3D surveys including beneath overhangs and within crevices and caves, (ii) freezing of motion even such as of highly-mobile water surfaces by using time-synchronised multiple cameras, (iii) change detection and improved process-form relationships and thus 'mechanistic segregation'.

Advances linked mainly to SfM-MVS photogrammetry workflow	Advances linked mainly to (image acquisition method) UAV/drone development
• Democratised 3D topography surveys; inexpert operation of hardware and software • Spatial density rivalling that of LiDAR or MBES • Point precision and accuracy rivalling that of LiDAR or MBES • Automatic generation of orthophotograph (stereo-photogrammetry can also do this) • Spans spatial scales • Archival analysis • Repeatable and attractive for repeat surveys and thus change detection	• Low financial cost acquisition • Very fast acquisition • Spatial coverage rivalling that of LiDAR or MBES • Direct georeferencing

Table 2. Attribution of recent advances in knowledge and understanding in the fluvial and aquatic sciences due both to the uptake of SfM workflows and to the co-evolution of consumer grade UAV/drone technology. For quantified properties of these surveys see Table 1.

Recent studies have realised the potential of relatively seamless surveys that stretch across multiple scales; from reach- to patch- to grain-scale. *Subaerial* grain scale to landscape scale applications of SfM predominate. There has been some success with *through-water* imaging but the resultant distortion and colour saturation problems mean that these are a focus of ongoing and emerging developments in processing. *Underwater* applications have made novel measurement and interpretation of complex topography and objects, especially coral reefs and organisms, respectively. The latter is particularly notable for determining organism health (via colour) and organism age (via geometry) and even organism behaviour (via motion). Generally, fluvial and aquatic applications of SfM have developed separately but there is clearly great potential for better integration and sharing of methodologies between these two sub-disciplines.

Whilst writing this review, we have noted legislation worldwide being tightened around UAV usage. No-fly zones are being designated and more and more often research using UAVs is deemed to fall under a commercial licencing control. These changes are not prohibitive to drone-based acquisition of images for SfM but they demand more careful planning and perhaps a longer lead-in time to campaigns and a larger financial budget.

Looking farther into the future, SfM workflows could be applied with some modification to high-resolution satellite images[115], which are becoming especially attractive to geoscientists for being freely available and with daily repeat coverage (e.g. Planet imagery: https://www.planet.com/). However, the modifications required for SfM workflows to use satellite imagery are not trivial because the perspective camera model used by SfM is incompatible with the way satellite imagers are designed. Thus that development cost will have to be mindful of the improving spatio-temporal availability and quality of spaceborne LiDAR data.

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