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Advanced methods to investigate hydro-morphological processes in open-water environments

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Abstract

Hydro-morphology describes the interactions between water and sediments in fluvial systems and the corresponding processes across all spatial and temporal scales. The results are natural and anthropogenically influenced bed structures and fluvial landforms. However, many of these hydro-morphological processes cannot be described analytically yet, as a result of their stochastic behaviour and the multitude of processes involved across spatial and temporal scales. Deeper knowledge of these processes is essential, not only for understanding the system itself, but also for practical applications, which rely on correct and reliable investigations of these processes. During the European Geoscience Union (EGU) General Assembly (GA) 2018 in Vienna, Austria, the conveners of the session on "Measurements, monitoring and numerical modelling of sedimentary and hydro-morphological processes in open-water environments" had the idea of initiating a special issue, containing a collection of recent achievements in this research field. The aim of this extended introduction is twofold. First, an overview on research needs in investigating hydro-morphological processes in open-water environments is given in this article. Second, recently published studies that aim to improve the understanding of hydro-morphological processes in rivers, lakes and reservoirs by innovative measurement approaches are discussed. In addition to submitted papers collected from the EGU GA in 2017, 2018 and 2019, related studies published in *Earth Surface Processes and Landforms* (*ESPL*) over the last two years are also incorporated into this special issue. The papers selected cover a wide range of studies with differing spatial and temporal resolutions. This broad spectrum of different scales clearly indicates the challenges associated with the development and use of advanced methods for investigating hydro-morphological processes in open-water environments.

KEYWORDS
advanced measurement methods, field investigations, hydro-morphological processes, laboratory investigations, open-water environments, sediment transport

1 | INTRODUCTION

Natural fluvial systems and landforms are formed by hydro-morphological processes, which describe the interactions between the hydraulic characteristics of the water body and the available sediments across all spatial and temporal scales. Hence, understanding processes such as entrainment, transport and deposition, conditioning river channel morphology and bed composition is a key feature of various research disciplines such as geomorphology and palaeoclimatology or hydraulics and river engineering. An accurate evaluation of these hydro-morphological processes is fundamental for the adequate development of conceptual sediment budget models,

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the calibration and validation of numerical tools or evaluations of the effects of human interventions. As a consequence, many research tasks as well as practical applications rely on correct and reliable investigations of hydro-morphological processes (e.g. Haun et al., 2017; Vanoni, 1975).

With respect to their hydro-morphology, natural systems can be characterized by long-term equilibrium conditions of sedimentation and erosion processes (Lane, 1955). Nevertheless, even if these equilibrium conditions do not lead to any significant changes of the bed levels in the long term (10–50 years), within short periods (1–10 years) natural systems can be characterised as highly dynamic. This is the result of the changing hydraulic conditions and the given boundary resistance of the bed, which is also highly influenced by sediments coming from the catchment. These dynamic conditions and the resulting heterogeneity of the water body provide a suitable habitat for many species, for example fish or macrozoobenthos, and subsequently good ecological conditions (e.g. Gayraud & Philippe, 2003). However, anthropogenic interventions within the fluvial system often lead to an altered system, resulting in changes in hydro-morphological conditions. Taking a river as an example, anthropogenic interventions, such as the implementation of lateral structures or riverbank fixations, may lead to a system with static equilibrium conditions. As a direct consequence, hardly any changes in the riverbed morphology, in both the long and short term, can be seen. This inevitably leads to a reduced ecological functionality of the system. When the status of such an imbalanced river is described, a distinction is often made between *supply-limited systems* and *transport-limited systems*. Within a supply-limited system, the sediment supply (extrinsic factor) is smaller than the transport capacity of the river (intrinsic factor), resulting in riverbed degradation. In a transport-limited system, the sediment supply exceeds the transport capacity of the watercourse, resulting in riverbed accumulation. In both cases, an adaption of the intrinsic factors of the river, for example slope, river shape or width, will occur until new equilibrium conditions are reached. In addition, we face the occurrence of more extreme climate-related events, transformations of rural landscapes and unsustainable urban population growth, which continuously change the conditions within and along water bodies as well as within catchments. To ensure hydro-morphologically (but also ecologically) sustainable modifications of fluvial systems, it is fundamental to understand and predict sedimentary and hydro-morphological processes in open-water environments.

Investigating hydro-morphological processes in open-water environments, such as rivers, estuaries as well as lakes and reservoirs, is not trivial. On the one hand, different spatial and temporal scales must be considered, and on the other hand, many of the processes involved have strongly stochastic elements (van Rijn, 1993; Van Prooijen & Winterwerp, 2010; Haun, Camenen, & Sumi, 2017). An example of this is the collision of small sediment particles (clay and silt) within the water column, resulting in the formation of flocs (a micro-scale process). These generated flocs have a completely different shape, density and settling behaviour, compared with the original particles, which may further change their transport, settling, but also consolidation behaviour (Hillebrand, 2008; Harb, 2013). Analytical approaches for predicting such aggregation and disaggregation processes are not yet available, which is also a result of the as-yet-unravelled physico-chemical and biological interactions of small sediment particles (Klassen, 2017). In this case, changes in the hydraulics within fluvial systems may promote or prevent ongoing aggregation and disaggregation processes and thereby have a direct influence on the ongoing morphodynamics. However, in other cases, the opposite may apply, and sediment-transport-related processes, such as the generation of riverbed structures and fluvial landforms (a macro-scale process), influence the hydraulic conditions as a result of the changing roughness of the riverbed (Einstein & Barbarossa, 1952; Engelund & Hansen, 1967; Ferreira et al., 2012). Bed structures, such as bedforms, are also the governing type of bedload transport for a wide range of discharges and grain sizes (e.g., sand) (Tsubaki et al., 2018; Wieprecht, 2001; Zanke, 1982), even if bedload transport is often characterised only by a sliding, rolling or jumping transport behaviour of single particles (sand, gravel and stones) (Einstein, Anderson, & Johnson, 1940; van Rijn, 1984). However, bedload transport in particular is characterised by a high spatial and temporal variety, as the processes involved are highly stochastic and both the available sediment and its transport depend strongly on the hydraulic conditions in the river. As a result of the so-far-unravelled processes behind bedload transport, different empirical developed formulae are used in practical applications, being based on (i) excess shear stress (e.g., Meyer-Peter & Müller, 1948; Parker, 1990; van Rijn, 1984), (ii) stream power (e.g., Bagnold, 1966; Yang, 1984) or (iii) stochastics (e.g., Einstein, 1950; Yalin, 1977).

To be able to better frame the outcomes of the individual articles gathered in this special issue, we provide in this first part a review on the status of unsolved problems in fluvial sediment transport. The different individual processes of sediment dynamics are grouped and discussed on the basis of the entrainment, transport, deposition and consolidation (ETDC) cycle (Maggi, 2005).

In the second part, the development of methods to investigate (measure) ongoing hydro-morphological processes is presented based on selected papers and with the aim of providing process-based understanding. As hydro-morphological processes act on different spatial and temporal scales, a broad range of scales is covered. These studies range from laboratory experiments with an investigated surface area of only 10 mm^2 and a measurement rate of 10 Hz, to investigations on a larger scale, in which areas up to 5.25 km^2 are investigated and observations cover time spans of several years.

2 | RESEARCH NEEDS IN INVESTIGATING HYDRO-MORPHOLOGICAL PROCESSES

Understanding hydro-morphological processes in complex water–sediment systems is essential for the sustainable management of aquatic systems in the future. However, although an increasing number of high-quality studies that aim to unravel the fundamentals behind hydro-morphological processes are available, knowledge gaps still exist. One of the main reasons is that we still lack measurement methods that can capture the wide range of processes occurring in water bodies, with their high temporal and spatial variability.

In this introduction to the special issue "Advanced methods to investigate hydro-morphological processes in open-water environments," we aim to provide an overview on open research questions, with a special focus on the development of measurement methods and approaches. However, we are aware that this review is incomplete and should only be considered the basis for further efforts to outline research requirements. The aim is mainly to present the variety of existing open research questions as well as their diversity with respect to space and time.

2.1 | Entrainment of sediments

The entrainment of a single non-cohesive grain can be described in the ideal case by the sum of forces acting on this particle. As soon as the moments of the driving forces become larger than the moments of the stabilizing forces, the particle will be eroded (e.g. Yalin, 1977). However, in open-water environments, the entrainment process is influenced by additional sediment-related factors, such as grain sorting, bulk density or cohesion, as well as by hydraulic boundary conditions, which are highly variable in space and time. Hence, advanced measurement methods are necessary to investigate the hydraulic boundary conditions close to the bed and thereby obtain three-dimensional velocities and turbulence characteristics. Although such quantification of near-bed flows in rough-bed open-water environments is available from measurements conducted in research flumes (e.g., Dey, Paul, Fang, et al., 2020; Li & Li, 2020; Lyn, 1993), large-scale or in situ investigations are still rare. As a result, often temporally (but also spatially) averaged flow characteristics are used when predicting hydro-morphological processes (Dey, Paul, & Padhi, 2020; Franca et al., 2008; Manes et al., 2007; Mignot et al., 2009; Nikora, McEwan, et al., 2007; Nikora, McLean, et al., 2007). The entrainment of bed material also needs to be quantified, as a function of sediment-related factors for a set of given boundary conditions. Although the erosional behaviour of single non-cohesive sediment particles can be described and empirical relationships have been developed in the past, for example by Hjulström (1935), Schoklitsch (1935), Shields (1936) and Yang (1984), additional processes alter the erosion behaviour and must be quantified. Examples of these processes are the interaction of particles in sediment mixtures (Stelczer, 1981; Wilcock et al., 2001; Zanke, 1982), bed armouring processes (Harb, 2013; Jain, 1990; Parker et al., 1982), layering of sediment deposits (Blom, 2008; Parker, 1991; Parker et al., 2000) and riverbed clogging (Cunningham et al., 1987; Einstein, 1968; Schälchli, 1992). However, measuring all of the above-mentioned phenomena remains challenging. Riverbed clogging, for instance, which describes the process of infiltration and accumulation of fine sediments in pores of gravel-bed rivers, not only increases the stability of the bed but also limits the hydraulic conductivity and influences the exchange process between surface and sub-surface flow (e.g. Heywood & Walling, 2007; Mayar et al., 2020; Noack et al., 2017; Schälchli, 1992), with a subsequent negative environmental impact. However, a deeper investigation of colmation is still not possible, due to the lack of appropriate qualitative investigation methods (Harper et al., 2017; Holzapfel et al., 2020; Seitz et al., 2019).

As soon as cohesive sediments become involved in the entrainment process, physico-chemical as well as biological processes interact and change the erosional behaviour of sediment deposits significantly (Grabowski et al., 2011). As a result of inter-particle binding forces (cohesion), in combination with adhesion, the critical shear stress of fine sediments may be up to 50 times larger compared with particles of similar arithmetic mean sizes without cohesion and adhesion forces (Black et al., 2002; Kothyari & Jain, 2010; Righetti & Lucarelli, 2010). Black & Paterson (1997) provided an overview on existing in situ devices to investigate cohesive sediments, where in general two groups exist, namely benthic flumes and miscellaneous devices (Aberle, 2008; Aberle et al., 2017). However, all devices are characterised by limited spatial resolution and often provide only the possibility of quantifying erosion thresholds of cohesive/non-cohesive sediment mixtures, without providing additional knowledge regarding the resuspension of cohesive sediments (e.g., by Beckers et al., 2020; Berlamont et al., 1993; Gerbersdorf et al., 2007; Kamphuis & Hall, 1983; Mehta et al., 1989; Noack et al., 2015; Shao & Lu, 2000; Schäfer Rodrigues Silva et al., 2018).

2.2 | Sediment transport processes

Sediment transport processes can generally be sub-divided into transport within the water column (suspended sediment transport) and transport along the bed by sliding, gliding or saltation (bedload transport) (e.g., Einstein et al., 1940; van Rijn, 1984). The dimensionless number derived by Rouse (1937) is often used to determine the vertical distribution (concentration profile) of suspended sediments and thereby the form of sediment transport. It can be assumed that suspended sediment transport represents the main share of the transported sediments in water bodies. Morris & Fan (1998) assumed that around 15% of the total sediment load in rivers is transported as bedload. Maddock & Whitney (1950) differentiated between water bodies dominated by sand and gravel or by rock, with values of transported bedload of 0–20% and 2–8%, respectively. The main reason for the uncertainty in these numbers is the lack of measurement data, especially for sediments transported as bedload.

Although it may be assumed that suspended matter is easier to quantify as a result of its more homogeneous transport mode (convection and diffusion) compared with bedload (stochastic behaviour) (Muste et al., 2016), mainly direct measurement methods, with limited spatial and temporal resolution, are used in practice. However, indirect methods are becoming more common, for example based on optics (e.g., turbidity meters or devices based on laser diffraction; Ankers et al., 2003; Czuba et al., 2015; Haun et al., 2015; Minella et al., 2008) or acoustics (acoustic Doppler current profilers, ADCPs), and these can enable higher spatial and temporal resolution (Aleixo et al., 2020; Baranya & Józsa, 2013; Ehrbar et al., 2017; Haun & Lizano, 2018; Guerrero & Di Federico, 2018; Guerrero et al., 2016, 2017; Latosinski et al., 2014). However, processes such as flocculation or the occurrence of organic content within the water column influence not only the behaviour of transported particles but also the measurements themselve, when based for example on optics (Haun et al., 2015). Investigating short-term and partly very local processes, such as density-driven transport in reservoirs, lakes and estuaries, is another advantage for existing measurement techniques, as density currents occur near the bottom, where for example devices based on acoustics have limitations due to blanking distances close to the bottom as a result of side-lobe effects (Haun & Lizano, 2018; Muste et al., 2006).

Although bedload contributes a smaller share of total transported sediments, for conditioning river channel morphology and bed composition, investigations of bedload transport provide fundamental knowledge that is also necessary for practical applications. However, reliable measurements of bedload are still challenging, due to the stochastic behaviour of the transport process itself and the fact that the transport often occurs in pulses rather than continuously. However, indirect methods, based for example on acoustics with ADCPs (Conevski et al., 2019, 2020) or geophones (Rickenmann et al., 2012; Rickenmann, 2017), can provide higher-resolution measurements and subsequently more possibilities for the future.

Sand fractions represent a special case in sediment transport. They are important for river morphology, but the quantification of the amount of sand entering the ocean is also of great importance, as it is assumed that around 20×10^9 tons of sediments are transported by rivers each year (Milliman & Farnsworth, 2011; Milliman & Syvitski, 1992; Walling & Webb, 1996). Quantifying the transport of sand particles is particularly challenging because they can be transported either in suspension or as bedload depending on the hydraulic boundary conditions. In such a case, bedforms may often become the governing type of bedload transport (Aberle et al., 2012; Wieprecht, 2001; Zanke, 1982).

2.3 | Sediment deposition

The deposition of sediments depends mainly on the settling velocity of transported particles, which is often described by using the Stokes law (Stokes, 1851), or the formulation given by Rouse (1937) or Rubey (1933). Most of these formulations were obtained for rounded sediments with a specific density. However, the settling velocity of particles depends strongly on their shape and density (Dietrich, 1982). Hence, fine sediments, and in particular cohesive particles, show a completely different settling behaviour compared with coarser sediments. On the one hand, this is a result of their high surface-to-volume ratio and, on the other hand, due to flocculation processes (Hillebrand, 2008). The formation of flocs is a result of the collision of small sediment particles within the water column and inter-particle interactions. In addition to water-related factors such as pH, salinity and the suspended sediment concentration in the fluid, physico-chemical and biological interactions also play a major role in this process, resulting in large uncertainties in predictability (Harb, 2013; Hoffmann et al., 2017; Klassen, 2017). The investigation of flocs is not trivial due to their fragility. Hence, optical devices, often also associated with low temporal and spatial resolution, have mainly been used in the laboratory and in situ to provide insight into flocculation processes (Klassen, 2017).

However, the settling behaviour of particles is also strongly correlated with the hydraulic conditions, namely the flow velocities and turbulence characteristics of the fluvial system. When the flow conditions change, for instance when a river enters a reservoir, lake or estuary, particles previously kept in suspension settle and subsequently deposit. Grain sorting can often be seen, where coarser particles start to settle first while finer particles are transported further into the lake or reservoir for example (Morris & Fan, 1998). In many cases, also the formation of a delta is visible as a result of the changing hydraulic conditions moving successively towards the dam (Annandale, 1987). This movement can only be investigated by periodic surveys with high spatial resolution, for example, by using side-scan sonars.

2.4 | Consolidation of deposited sediments

When sediments are deposited in reaches with low flow velocities and turbulence, consolidation processes appear as a result of the pressure induced by water and the weight of the particles themselves (e.g., Andrews, 2006; Been & Sills, 1981; Ockenden & Delo, 1988; Toorman, 1996; Winterwerp & van Kesteren, 2004). An important parameter for the consolidation of non-uniform sediment mixtures is, besides the pressure head, the distribution of the particles and thus the available pore space, which depends on the sorting coefficient and packing arrangement (e.g., Edge & Sills, 1989; Folk, 1968). In addition, deposition of flocs has great potential for consolidation, as flocs are usually fragile and result in loose-texture deposits with high water content and subsequently low density immediately after deposition. During consolidation, the flocs rearrange themselves and pore water is expelled, resulting in a denser bed structure (Torfs et al., 1996). A similar behaviour can be seen in the case of settled turbidity currents, which are driven by differences in density and by gravity (Batuca & Jordaan, 2000; Morris & Fan, 1998; Nogueira et al., 2014). Turbidity currents transport large amounts of sediments into lakes, reservoirs and estuaries and may transform into muddy lakes in front of the dam (reservoirs) or often the deepest point (lakes) (e.g., De Cesare, 2006; Schneider et al., 2012). However, the inclusion of gas and water plays an important role during consolidation, as well as the ongoing production of gas within the deposits (e.g., Peeters et al., 2019). Although the detailed processes of consolidation are not yet clear, consolidation effects may result in higher shear strength of the sediments by reducing their porosity and permeability (Gerbersdorf & Wieprecht, 2015; Harb, 2013; Mehta et al., 1989; Schäfer Rodrigues Silva et al., 2018). Although laboratory studies exist (e.g., Torfs et al., 1996; Van Rijn & Barth, 2019), detailed large-scale in situ measurements of for example bulk density or porosity are challenging and are often only performed with limited spatial resolution (Beckers et al., 2018; Blomqvist, 1985; Dück et al., 2019; McIntyre, 1971).

2.5 | Monitoring of sediment transport and morphological processes

Monitoring of sediment transport and morphological processes is implemented in open-water environments, either when a single ongoing process should be investigated to gain deeper knowledge on governing processes, or the behaviour of the system as a whole should be observed. Hence, on a temporal scale, short- and long-term monitoring are differentiated. However, short-term monitoring is not only used to understand single processes within the fluvial system, for example flow analysis or sediment mixing at river confluences (e.g. Baranya et al., 2015; Guillén-Ludeña et al., 2016), but also to investigate short-term events and their influence on the hydro-morphological system. One example is the observation of downstream suspended sediment concentrations during reservoir flushing, for example to quantify the amount of eroded sediments, or investigations on the hysteresis effect of water and transported sediments, for example during flood events (Hauer et al., 2020; Landers & Sturm, 2013; Muste et al., 2020). Long-term monitoring is often used to provide deeper understanding of the system itself. An example of this is the development of a sediment budget for a whole river stretch, which strongly depends on such long-term observations (Frings, Döring, et al., 2014; Frings, Gehres, et al., 2014). Thus, it is necessary to develop appropriate methods that enable high spatial but also temporal resolution, to provide further understanding on single processes, but also to investigate the whole fluvial network.

The use of indirect methods, for example based on acoustic and optical techniques, will enable measurements with much higher resolution in the future, but for investigations of whole river systems for example, their spatial resolution is still too low. Therefore, technologies such as unmanned aircraft systems (UAS) for meso-scale observations have already demonstrated their value to quantify the spatial and temporal evolution of the storage and transport of sediment as well as the landscape and morphological alteration by human interventions (Carbonneau & Dietrich, 2016; Cook, 2017; Hemmelder et al., 2018; Lane et al., 2020; Lejot et al., 2007; Rusnák et al., 2019; Tamminga et al., 2015). In addition non-intrusive methods, for example based on satellites images and remote sensing, have been used more often recently. Potential satellite products are mostly freely available for tracking, for example river morphology and landscape changes, or sediment plumes (e.g. Kilham et al., 2012; Ouillon, 2018; Pavelsky & Smith, 2009; Ritchie & Cooper, 1988; Wang et al., 2009). However, while remote-sensing technologies only measure the uppermost centimetres of the surface, the suspended load for instance follows the Rouse profile with maximum values at depth (Rouse, 1937). Hence, quantification studies to reduce the related uncertainties or to be used for calibration, such as ADCP measurements, which assess the sediment concentration over a depth profile, are still required.

Finally, a brief look into the future reveals the use of artificial intelligence (AI) machine learning, for example based on artificial neural networks (ANN), in hydro-environmental research (Demirci & Unes, 2015; Maier et al., 2014; Mustafa et al., 2012; Nicklow et al., 2009; Solomatine & Ostfeld, 2008; Unes et al., 2017). ANN approaches are particularly useful for rating curves (Liu et al., 2013) or modelling and forecasting the suspended sediments in rivers (Buyukyildiz & Kumcu, 2017; Demirci & Baltaci, 2013; Nivesh & Kumar, 2017). In addition, genetic algorithms, Bayesian networks or regression tree approaches are evolving, as summarised and reviewed by Goldstein et al. (2019). The availability of Big Data, especially from remote sensing, will enable the use of deep learning methods in the future, providing new opportunities in science, but also for practitioners (Savic, 2019; Shen, 2018). In addition, genetic algorithms and other forms of evolutionary computing have already found application in various fields, for example for optimal reservoir system operation (Maier et al., 2014; Nicklow et al., 2009). These new methods and possibilities derived from AI and Big Data will allow and aid enhanced instrumentation for non-resolved quantities in the future. However, most of these methods require data for training. Thus, an improved exchange of research data following the findable, accessible, interoperable and reusable (FAIR) principles (Wilkinson et al., 2016) will become increasingly important for the hydrological and geomorphological communities.

3 | RECENT RESEARCH INVESTIGATING HYDRO-MORPHOLOGICAL PROCESSES

A total of nine articles presenting recent achievements in the investigation of hydro-morphological processes by using advanced investigation methods are gathered together in this special issue. The articles are subdivided into field and laboratory studies and discussed from large- to small-scale processes.

3.1 | Advanced measurement methods for field investigations

Freely available satellite data offer great potential for fluvial studies, from regional to global scales. However, on local scales, the spatial resolution of satellite sensors is often too low to distinguish between water, sediment and vegetation. In addition, transition areas result in mixed pixels. Carbonneau et al. (2020) presented a fuzzy classification model using a convolutional neural network (CNN) to infer sub-pixel composition to compensate for small channel widths. A major challenge with this approach is the acquisition of suitable training data appropriate for machine learning models that can predict land-cover type information from image radiance values. Hence, unmanned aerial vehicles (UAVs) and Sentinel-2 imagery were used to develop a fuzzy classification approach suitable for large-scale investigations. The authors argue that the novel use of UAVs as a field validation tool for freely available satellite data can bridge the scale gap between local and regional fluvial studies.

Radiofrequency identification (RFID) technologies are widely used to implement tracers for investigating bedload transport and represent a step forward in sediment tracking. However, in river systems with active bedload transport or large water depth, low efficiency is often achieved as a result of the technical specifications. In their study, Cassel et al. (2020) deploy active ultra-high-frequency transponders (a-UHF tags) in combination with five different survey methods to investigate these combinations with respect to recovery rate, field effort, geopositioning error and efficiency. The results show that this a-UHF RFID technology allows rapid surveys over large areas, including emerged bars and shallow water channels, with a high percentage of recovery of tracers in combination with a low geopositioning error. In addition, it was shown that UAV-based surveys decrease the survey time and the error even further, while at the same time increasing efficiency.

As a result of the construction of dams, downstream river stretches are directly influenced by flow regulation and may switch to a supply-limited system. In their study, Stähly et al. (2020) investigated a novel multi-deposit method, in combination with defined environmental flows for activating the dynamics of the river morphology downstream of a dam. During the investigations, a flood was released from Rossens Dam in Switzerland in combination with a multi-deposit configuration of sediment replenishment. For validation, radiofrequency identification (RFID) passive integrated transponder (PIT) tags, implemented in stones, as well as a fixed antenna at the riverbed and a mobile antenna were used to enable an investigation of the erosion, transport and deposition of replenished sediments. A comparison of the results obtained in the field with those from laboratory experiments confirmed the robustness of the implemented multi-deposit sediment replenishment method.

As mentioned above, the construction of dams influences large gravel-bed rivers in terms of altering coarse transport regimes and river morphodynamics. Brenna et al. (2020) used data from a tracer-based monitoring programme, downstream of a recently constructed dam, to apply a virtual velocity approach to estimate the coarse bed material load at several river cross-sections. The results provide a new insight into the impacts of dam construction on streambed material mobility and the sediment regime. A longitudinal gradient of effects was observed in these investigations: Sections located closer to the dam could be characterised by more evident impacts due to deficits in coarse sediment input from upstream, whereas a partial recovery of sediment dynamics was observed at the sections located further downstream of the dam.

Secondary flow at river confluences results in spatial and temporal variation of the flow field and subsequent morphodynamic changes. To investigate secondary circulation, vessel-mounted ADCPs are increasingly being used. However, less attention is usually paid to the strong shear rates in the flow and an assumption of homogeneity between the measured radial components of velocity is made. Moradi et al. (2019) applied a newly established method on data from repeated moving ADCP measurements and compared the results with those from existing data processing approaches. The comparison of the processed data confirmed that the newly presented method produces different results from more conventional approaches. Hence, the authors concluded that, in the future, both methods should be applied to identify where data analysis might be impacted by strong shear and where inferences of secondary circulation may need to be considered more precisely.

3.2 | Advanced measurement methods for laboratory investigations

In a laboratory study, Plumb et al. (2020) investigated how urbanization-induced changes in flow regime as well as hydrograph shape impact bedload transport and the resulting bed morphology. Pre-urbanization conditions correspond to a longer duration of hydrographs, and lower rates of unsteadiness until reaching the peak discharge. Photographic-derived surface textures show enhanced surface armouring during these pre-urbanization conditions, speculated to be a result of the longer time available for bed rearrangements to occur. In contrast, urban conditions correspond to a shorter duration of hydrographs, which displayed more time above critical shear stress thresholds, and leading to higher bedload transport rates and ultimately to more variable hysteresis patterns. These newly established conditions result in larger channel adjustments with respect to slope, topographic variability and surface texture.

The stability of fine sediment depositions is important information for the sustainable management of aquatic environments. As a result of the presence of physico-chemical and biological interactions between fine sediment particles, with a high surface-to-volume ratio, the prediction of cohesive sediment erosion represents a special challenge. Beckers et al. (2020) developed a laboratory method to observe the erosion process of cohesive sediments in a way that made it possible to distinguish between individual emerging erosion spots and the erosion of detached aggregate chunks, resulting in large holes, but also to observe processes, such as the propagation of the erosion of already affected areas in all directions. The authors concluded that, with the developed measurement technique, future measurements will allow the determination of spatio-temporal erosion variability and erosion rates for selected time periods with high resolution.

High-energy events, such as tsunamis, have sufficient power to transport boulders inland. However, the uncertainties in the transport models presented and used in the literature are widely acknowledged. Bressan et al. (2018) studied the minimum flow conditions for boulder transport by using laboratory experiments. The most important result of their study is that boulders already move when only partially submerged by the flow. This suggests that the drag and lift coefficients, commonly used in the literature, are not adequate to correctly estimate the minimum conditions for transport and need to be adapted. For the assessment of uncertainty, the authors introduced dynamic thresholds, separating three distinct regimes, where transport of boulders: (i) is impossible, (ii) is certain and (iii) is possible depending only on the actual turbulence bursts (intermediate stage).

An accurate simulation of particle entrainment is a key factor for predicting the quantity and quality of sediments available for transport. While grain-scale incipient motion is currently mostly simulated with two-dimensional (2D) particle geometries, Voepel et al. (2019) developed a vector-based fully three-dimensional (3D) grain rotation entrainment model. This model enables the inclusion of complexities of real grains, including grain shape, cohesion and the angle of entrainment relative to the flow direction in future studies. Both two-dimensional (2D) and three-dimensional (3D) simulations were compared with X-ray computed tomography. The results of this comparison show that the 2D approach produces estimates of dimensionless critical shear stress that are an order of magnitude lower than in the 3D model, which demonstrates sources of geometric error inherent in 2D models.

4 | CONCLUSIONS

This extended introduction to this special issue shows that the open research questions on hydro-morphological processes in open-water environments are manifold. To gain deeper knowledge on entrainment, transport, deposition and consolidation of sediments, further research is required. However, this understanding is fundamental for the sustainable development of open-water environments, especially when considering the challenges that will be faced in the future as a result of global change.

The aim of this special issue is to bring together studies applying advanced measurement techniques and novel monitoring concepts, which are crucial to determine sedimentary and hydro-morphological processes in rivers, lakes and reservoirs. The presented studies involve fundamental research in the laboratory to investigate the incipient motion of large boulders, also in cases when they are only partially submerged, the erosion behaviour of cohesive sediment erosion with high spatio-temporal resolution or the impact of hydrograph variability and frequency on sediment transport dynamics and riverbed morphology. Within large-scale studies of natural systems, new and advanced methods, such as the evaluation of ADCP processing options, UAV-based training of Sentinel-2 fluvial scenes or a-UHF artificial tracer mobility monitoring, are presented. In addition, methods to investigate hydro-morphological processes as a result of human intervention, such as the construction of dams or subsequent sediment replenishment under flood conditions, are presented together with a developed vector-based 3D grain entrainment model. Within this special issue, nine contributions of novel measurement techniques are discussed, providing not only an overview on the broad spectrum of work ongoing in the field of sediment research, but enable the possibility to provide further and deeper insight into the complex physical processes in hydro-morphology. Within the presented studies, not only the research methodologies, from flume to in situ studies, the temporal and spatial scales, but also the sediment characteristics (from coarse sediments to cohesive sediment deposits) differ, which is an indicator of the varied hydro-morphological processes occurring in open-water environments. All the selected articles are in themselves single pieces with the goal of providing further knowledge in the field of hydro-morphology to understand the complex processes behind sediment movement and sediment continuity in aquatic systems. In the future, besides the development of measurement techniques, advanced methods to analyse data will be necessary, including spatial heterogeneity, temporal significant changes, as well as the fuzziness and stochastic behaviour.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest.

AUTHORS CONTRIBUTIONS

Both authors contributed equally to this paper.

DATA AVAILABILITY STATEMENT

For this submission no additional data are available.

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