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Qualitative and quantitative acoustic mapping of bedform dynamics

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ABSTRACT

The qualitative and quantitative assessment of bedform dynamics has been a continuous challenge for conventional river monitoring methods due to the vexing problems associated with the limited capabilities to observe the bedforms in-situ and the intrusive nature of the instruments used for quantification of their movement. The advent of the new generation of acoustic- and image-based instruments has brought considerable promise for the experimental investigations in this area by allowing observations of the bedforms from close range along with possibilities of non-intrusive quantification of their movement with unprecedented spatial and temporal resolutions.

This paper reports proof-of-concept tests for quantifying the dynamics of the bedform migration using a combination of concepts from two representatives of the new nonintrusive instruments: acoustic survey and processing techniques associated with particle image velocimetry. Given the combination of mapping and velocimetry operating principles, we call the technique acoustic mapping velocimetry (AMV). This hybrid technique has potential to track the planar migration of the bedform and quantify the velocity of the moving bedform fronts. Described herein is a laboratory experiment illustrating the implementation of the AMV concept for quantifying bedform migration.

1. Overview

Knowledge of sediment dynamics in rivers is of critical importance for several practical aspects. Collectively, processes such as the scouring, deposition, and transport of sediment have a direct influence on fluvial navigation, water supply, hydropower plant efficiency, and the health of the aquatic ecosystems. Despite the relevance of the sediment-related problems for the hydrodynamics and morphodynamics of riverine environment, monitoring of sediment transport remains a major and challenging issue for river engineers due to the complex nature of the processes involved, their spatio-temporal variation, and the limitation of the current measurement technology [31]. Sediment transport is typically investigated with different analytical and observational tools for the sediment in suspension and the sediment moving in layers over the stream bed as bedforms. The current discussion focuses on the later processes.

Most of the natural streams convey bed sediment through different size of bedforms, from ripples to dunes. Einstein [8] defines bedload transport as the movement of sediment particles in a thin layer about two particle diameters thick above the bed by sliding, rolling, and making jumps with a longitudinal distance of a few particle diameters. Measurement of bedload transport rate in sand bed rivers with conventional sampling methods, such as pressure-difference samplers, e.g. Helley-Smith [19], is exceedingly high in terms of time and cost as the full characterization of the bedload across the stream calls for a large number of samples distributed in space and time. Moreover, no measurement method is universally accepted yet by the community and there is no standard against which to compare the measurement outcome. Alternatively, surrogate technologies are typically employed to monitor bedload transport as reported by Gray et al. [14].

Given the contemporary importance of informing on the anthropogenic-induced changes in sediment transport (such erosion due to intensive agriculture), there is a pressing need for developing methodologies of quantifying bedload transport that are consistent, repeatable, and can be used for closing the sediment balance at the watershed scale. Since 1980s', the advent of the acoustic technology for measurements in riverine environment have brought unprecedented capabilities to accurately measure and resolve bathymetric features over space and time [39]. These advancements renewed the search for new means to quantify the dynamics of the bed movement and bedload characteristics.

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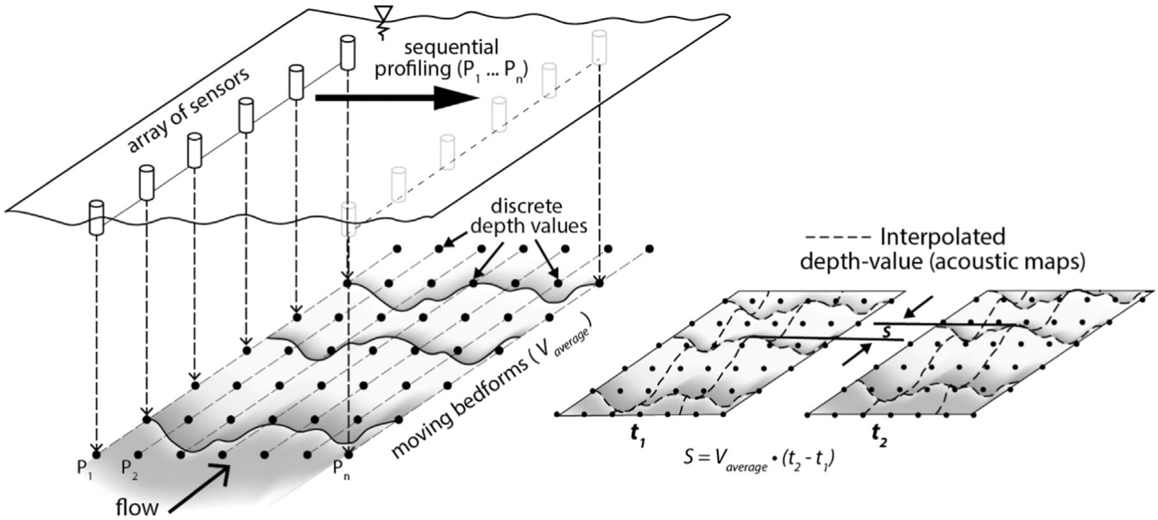

Fig. 1. Schematic of the process leading to the creation of acoustic maps using an array of acoustic sensors [31].

Recent investigations along this line are those conducted by Rennie et al. [37], Rennie and Millar [35,36] with Doppler current profilers and those of [21] with sonars. These new approaches are defined by Gray et al. [14] as: "Instruments coupled with operational and analytical methodologies that enable acquisition of temporally and (or) spatially dense fluvial-sediment data sets without the need for routine collection and analysis of physical samples other than for periodic calibration purposes". In essence, the methods consist of measurements of virtual bedload velocities that, in conjunction with a known bedload layer thickness, can provide estimations of the bedload rate using analytical formula such as those described by van Rijn [42]. The bedload layer thickness is typically estimated with analytical definitions (e.g., [13]) or empirical formulas based on the grain diameter of the bed specifications [8].

Taking advantage of the increased resolution, accuracy, and operational efficiency of the acoustic technologies, attempts are made to acquire streamwise bed profiles or to map the bathymetry over short river reaches at repeated time intervals to estimate bedload rates. Two approaches can be distinguished in these attempts for acoustic mapping technology. One is the tracking of the volumetric change due to bedform migration (e.g., [1,7,17]). The other approach determines directly the velocity of the dune crest [38] or the whole-field velocities associated with the dune movement (e.g., [31]). The second approach is used in the present paper for quantification of the bedform dynamics. The mapping methods can be used in conjunction with the Exner equation to derive the bedload as this equation requires estimation of the migration velocity of the bedforms [9]. The conventional method for estimation of bedform velocity assumes the dune shape as a uniform two-dimensional shape propagating downstream. With this assumption, the velocity can be estimated by observing the dune height variation at one point on the bed. However, the bedforms are highly variable across the cross-section in terms of dune length, height and migration velocities, hence a three-dimensional measurement protocol such as provided by the second approach would be considerably more realistic.

This paper reports initial experiments that combine concepts from two representatives of the new nonintrusive instruments for mapping the bedform and their spatio-temporal evolution and, as a by-product, the estimation of velocities of the bedforms migrating on an open-channel bottom. The mapping is obtained with acoustic survey and the velocity of the bedform fronts is obtained with processing techniques associated with image-velocimetry and GIS-based processing techniques. Given this combination of operating principles, we call this technique acoustic mapping velocimetry (AMV). The hybrid technique has capabilities of tracking bedform migration in the streamwise direction (i.e, bedload) or can monitor the lateral bedform movement (e.g., scour in development) in laboratory or field conditions if appropriate set of instruments are used for acquiring the measurements.

2. AMV process

Implementation of the AMV concept entails two phases. In the first step the acoustic maps are created as a continuous depth-data layer covering the target area on the open-channel bottom. Depending on the implementation site (i.e., field or laboratory), there are various alternatives to choose from in terms instruments to create these maps and map generation protocols. The choice of mapping instruments for field conditions includes single or multibeam echo-sounders (i.e., MBES) as well as Acoustic Doppler Current Profilers (ADCPs). These acoustic instruments entail one or multiple acoustic sensors that measure the depth at a point (single-beam sonar), along a line (multi-beam echo-sounder), or over multiple scattered points (ADCP). For laboratory conditions there are also more choices for bedform mapping (e.g., ultrasonic, laser, photogrammetry).

A multi-sensor acoustic sensor arrangement is selected for the present experiments as illustrated in Fig. 1 [31]. The sensor array collects simultaneous depth measurements with sensors distributed along a line for a short time interval, followed by immediate relocation of the sensor(s) at another adjacent location. The duration of the data collection for a set position, called herein for convenience profile, is dictated by the instrument accuracy, the flow conditions at the measurement site, and attained sufficient number of repeated measurements to smoothen out the scattering of small datasets. The relocation should be made incrementally using a pre-established spatial sampling pattern such that the time for covering the interested area to be the shortest feasible. The depth measurements resulted from the acquisition of the adjacent profiles create a cloud of bed-elevation points sampled non-intrusively on the bottom of the water body. With sufficient bed-sampling density, the individual discrete depth measurements can be interpolated to lend a map of the channel bottom.

There are several considerations that need to be fulfilled during data acquisitions for accurate mapping of the bedforms. Irrespective of the experimental situation (i.e., laboratory or field conditions), these considerations entail knowledge about the bedform