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Integrated automatic and continuous bedload monitoring in gravel bed rivers

Helmut Habersack [a,*], Andrea Kreisler [a], Rolf Rindler [a], Johann Aigner [a], Hugo Seitz [a], Marcel Liedermann [a], Jonathan B. Laronne [b]

[a] Christian Doppler Laboratory for Advanced Methods in River Monitoring, Modelling and Engineering, Institute of Water Management, Hydrology and Hydraulic Engineering, Department of Water–Atmosphere–Environment, BOKU – University of Natural Resources and Life Sciences Vienna, Muthgasse 107, 1190 Vienna, Austria

[b] Department of Geography & Environmental Development, Ben Gurion University of the Negev, Beer Sheva 84105, Israel

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ABSTRACT

Bedload monitoring techniques have been developed and applied for many years in rivers ranging from steep mountain torrents to the large gravel-bed Danube River in Austria. Most monitoring stations use a combination of direct (mobile bag samplers, slot samplers) and indirect (geophones, hydrophones) measurement methods. Each individual technique is adequate, yet features particular boundary conditions and limitations related to hydraulic and sampling efficiency, functionality during floods, sampling duration or grain size. We show the capabilities and limitations of the different monitoring devices with respect to technical, operational and economic criteria, evaluating their suitability for determining bedload transport parameters. Bedload monitoring results of a measuring site at the Drau River in Carinthia/Austria are used to illustrate the specific range of the device application. We present an integrated automatic and continuous bedload monitoring system. It complements the specific limitations of single monitoring methods by additional measurement devices, enabling comprehensive monitoring of the bedload transport process. We then derive the Bedload Discharge Integrated Calculation Approach and the Bedload Rating Curve Approach and discuss their application for determining bedload discharge Q_b and total bedload mass V_b. Whereas the integrated approach combines data from direct monitoring methods with indirect techniques, the rating curve approach uses only data from direct bedload monitoring devices. We demonstrate that applying an integrated automatic and continuous bedload monitoring system and combining the Bedload Discharge Integrated Calculation Approach and Bedload Rating Curve Approach yields accurate bedload discharge results.

1. Introduction

1.1. Aims of bedload monitoring

Bedload transport is a fundamental factor in determining the morphologic development of alluvial river reaches. Fluvial problems associated with sediment transport are related to a lack or surplus of bedload and/or to negative influences produced by anthropogenic interference with natural processes (Habersack, 1997). Since bedload transport shows a significant spatio-temporal variability (Einstein, 1937; Habersack et al., 2001a, Habersack et al., 2008, Laronne et al., 2003, Vericat et al., 2006, Rennie and Church, 2010, Francalanci et al., 2013), the choice of the most accurate measuring system is often difficult and depends on many parameters. In recent years, significant progress has been made with respect to indirect bedload monitoring techniques. This has involved the development of geophones, hydrophones (Belleudy et al., 2010a, 2010b; Habersack et al., 2010; Mizuyama et al., 2010a; Rickenmann et al., 2014; Rickenmann, in press) and other surrogate bedload monitoring techniques (Gray et al., 2010), including seismic monitoring of bedload (e.g., Burtin et al., 2011). Key parameters that characterize bedload transport include specific bedload discharge q_b [kg m^{-1} s^{-1}], local bedload discharge measured or calculated at the verticals in a cross section, bedload discharge Q_b [kg s^{-1}], total bedload mass V_b [kg], spatial and temporal variability of bedload discharge, initiation of motion and grain size distribution. Further, transport paths [m, coordinates], total transport length [m], step lengths, rest periods [m, s], burial depths [m] and transport velocity [m s^{-1}] are important.

1.2. Monitoring methods

Bedload monitoring methods can be divided into direct monitoring methods and indirect methods (Habersack et al., 2010). Here, we provide a short overview of commonly used bedload monitoring methods.

* Corresponding author.
E-mail address: helmut.habersack@boku.ac.at (H. Habersack).

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1.2.1. Direct monitoring methods

Mobile bag samplers have been used in gravel bed rivers for decades (Ehrenberger, 1931; Mühlhofer, 1933). For the purpose of this study, the category of bag samplers encompasses all samplers that are deployed handheld, cable suspended, or fastened on the channel bed and that collect bedload in a bag. Due to their relative low cost, broad range of experience and easy handling, they are often favoured for bedload sampling. Depending on the operational possibilities, these bedload samplers are either lowered to the riverbed from a bridge using a cable winch mounted on a trailer or with the support of a mobile crane. These devices enable determining specific bedload discharge q_b and cross-sectional discharge Q_b. Applying bag samplers at various river types often requires adapting the measurement procedure and constructing bag samplers for individual monitoring stations (Bunte et al., 2004; Bunte and Abt, 2005; Bunte et al., 2008; Kreisler et al., 2011).

The direct measurement of bedload discharge using *bedload slot samplers*, which are installed in the stream bed, enables determining the specific bedload discharge q_b. Two types of slot samplers can be differentiated: those in which the slot is perpendicular to the mean flow direction and spans the entire stream cross-section, and those in which the measuring slot is oriented parallel to the mean flow direction (Reid et al., 1980; Habersack, 1997). The slot sampler consists of a sample container covered by a slotted plate and inserted in a concrete pit in the riverbed. Moving bedload particles that fall through the slot into the container box are automatically weighed. The original Reid sampler uses a water-filled rubber pressure pillow beneath the sample container (Reid et al., 1980). The pillow responds to the accumulating bedload and overlying water column (Lewis, 1991). Such slot samplers have been used under various conditions in Mississippi, United States (Kuhnle, 1992), United Kingdom (Harris and Richards, 1995), in Israel (Laronne et al., 1992; Cohen and Laronne, 2005) and in several rivers in Spain (Riberia Salada stream, Vericat and Batalla (2010), Garcia et al. (2000), Lucia et al. (2013)) and France (Liébault et al., 2012). Furthermore, about 10 slot samplers were installed in Japanese Alpine rivers (Mizuyama et al., 2010a). Design modifications to the Birkbeck bedload sampler have been suggested (Bergman et al. (2007). First-ever deployment of a Reid type slot sampler in a large perennial gravel-bed river (Drau River, Austria) necessitated a comparably large sampling capacity and waterproofing the data-logging unit (Habersack et al., 2001). The bedload slot sampler in the Drau River, Austria (Habersack et al., 2001) was replaced in 2006 and 2008 by three bedload slot samplers that measure mass increase using load cells. Two of these bedload samplers are fixed in the river bed. The third one can be hydraulically lifted above the water surface.

1.2.2. Indirect, surrogate bedload monitoring methods

Recent advances in the development of non-invasive indirect bedload monitoring methods have been fuelled by the need for temporally high-resolution bedload monitoring data and automatic measurement procedures. The importance of surrogate indirect methods was emphasized at the International Bedload Surrogate Monitoring Workshop in 2007 (Gray et al., 2010) and at the International Workshop of Acoustic and Seismic Monitoring of Bedload and Mass Movements (Rickenmann et al., 2013). Indirect measurement devices involve active and passive monitoring methods.

Passive sensors that are installed into the river bed in combination with plates or pipes include plate geophones and pipe hydrophones. Plate geophones are passive acoustic sensors stemming from seismic subsurface exploration. For bedload monitoring the sensors are fixed on the underside of steel plates, which are embedded in the stream bed. Bedload particles transported through the stream cross-section impact on the steel plate and produce vibrations which are detected by the geophones. The software analyses the raw signal, computes summarizing parameters and stores them every minute (Habersack et al., 2010; Rickenmann et al., 2014). Additionally it is possible to store the raw signal. Plate geophones are nowadays deployed in various streams. Rickenmann et al., 2014 overviewed of some of these field sites. Plate geophones are further applied, for example, at the Elwha River, USA (Hilldale et al., 2015) and at the Sulda River in Italy (Vignoli et al., 2016).

The Japanese pipe hydrophone (hereafter called pipe hydrophone), or termed acoustic pipe sensor by Dell'Agnese et al., 2014, consists of a microphone sensor attached to the end of a half-buried steel pipe. This pipe is installed transversally over the stream cross-section and has variable length (exposure to bedload) and a thin, 2–3-mm-thick pipe wall (Mizuyama et al., 2010a). The microphone within the air-filled pipe detects vibrations of air induced by the impact of bedload particles (Mizuyama et al., 2010a). The recorded vibrations are amplified and transmitted to a converter, which processes the signal through a 6-channel band-path filter; the channels allowing gradually larger sound amplification. Laboratory experiments (Mizuyama et al., 2010b) showed that the lower grain size limit that can be detected is 8 mm, although field experience demonstrates a 2–4 mm lower limit (Mizuyama et al., 2010b).

Hydrophones record the acoustic waves emitted by river environments, including sounds generated by the transport of bedload particles. Recently, a hydrophone (Bruël and Kjaer type 8103) was installed in the Drau River in Austria by using a stainless steel structure fixed on a concrete foundation in the river bed (Geay, 2013). Acoustic data were recorded at a rate of 500 kHZ at a 12-bit resolution.

We hypothesize that no single bedload monitoring technique can derive all parameters of interest listed in Section 1 with the requested accuracy and that only a combination of several devices can lead to results reflecting true transport processes as they occur in nature. In this paper we aim to assess the accuracy with which bedload discharge can be determined using an integrated automatic and continuous bedload monitoring system, taking advantage of the monitoring station on the Drau River (Austria).

2. The bedload monitoring station on the Drau River (Austria)

As part of the bedload monitoring stations in Austria (Fig. 1a, c) the focus of this paper is on the monitoring station Dellach - Drau in Carinthia where bedload transport process has been measured in its spatial and temporal variability since 1993. The first measurements at this station were performed with a large (15.2 cm intake) Helley-Smith sampler, followed by the first version of a bedload slot sampler (Habersack et al., 2001; Habersack and Laronne, 2002) and an analysis of the spatio-temporal variability of bedload discharge (Habersack et al., 2008). Further investigations compared textures of bedload to those of the bed material (Habersack and Laronne, 2001). The data of direct bedload measurements were used to evaluate bedload discharge formulae (Habersack and Laronne, 2002). In 1994 the first bedload slot sampler in a large gravel bed river was installed at the Dellach measuring site (Kreisler et al., 2014). The further development of the monitoring site with further bedload slot samplers (one of them liftable) and a plate geophone device is presented in this paper.

At Dellach the catchment area of the Drau River is 2131 km^2. The river has its origin in Italy, near the border with Austria and after a flow length of 748 km enters the Danube River at Osijek (Croatia). The Drau has a nivo-glacial discharge regime (Mader et al., 1996). The river is experiencing significant bed degradation of about 1 cm per year due to engineering works. At the measuring site the bed level is stable because of continued input of coarser sediments from nearby tributaries (Habersack et al., 2008). The measuring site is located approximately 27 km downstream of the confluence of the Drau and Isel Rivers (Fig. 1a). The mean annual discharge is 62.6 $m^3\ s^{-1}$, the 1 year flood event is 300 $m^3\ s^{-1}$ and the maximum observed discharge is 850 $m^3\ s^{-1}$ (Oberdrauburg, HD 1951–2012). At the measuring site the bed width at mean flow is about 50 m and bed slope about 0.18%. The characteristic grain sizes of the subsurface bed material are $d_{10} = 1.6$ mm, $d_{50} = 27.9$ mm, $d_{mean} = 38.7$ and $d_{90} = 95.3$ mm; the corresponding surface values are $d_{10} = 2.9$ mm, $d_{50} = 65.7$ mm, $d_{mean} = 61.8$ mm and $d_{90} = 113.2$ mm (Habersack and