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Bedload pulses in a hydropower affected alpine gravel bed river

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ABSTRACT

This study investigated the sediment resupply and transport dynamics at the Upper Drau River upstream of Lienz (Eastern Tyrol, Austria). Due to a hydropower plant, a 24 km long river reach of this alpine gravel bed river is under residual flow conditions, although sediment is still resupplied into the reach through many active torrents and tributaries. As a result, sediment deposition in the residual flow reach intensified, hence increasing maintenance efforts to stabilize this river section and ensure flood protection. In combination with a new sediment management program, a continuous bedload monitoring system was installed 2 km downstream of the residual reach in 2001 to support the development of adapted sediment management strategies. The surrogate bedload monitoring system consists of 16 impact plate geophones, installed over a 17 m wide cross section. The unprecedented 15-year dataset of high-resolution bedload intensity revealed a complex process of gravel storage and intermittent resupply from the residual reach, allowing the authors a detailed analysis of frequently occurring bedload pulses.

These transport features are triggered by increased discharges during floods in the residual reach and created pronounced anticlockwise bedload hysteresis or, with a temporal shift to the event peak, caused distinct shifts in the bedload activity downstream. Bedload pulses produce very high bedload fluxes while in transit, tend to increase bedload flux in the post-event phase, and can alter and reduce the upstream sediment storage leading to a lowering of bedload availability for future pulses. The observed time lags between main discharge events and the arrival of the macro-pulses are correlated with mean water discharge during pulse propagation, thus enabling a prediction of the pulse arrival at the monitoring station solely based on the hydrograph. In combination with the hydrological setup of the reach, the observed bedload pulse time lags allowed an estimation of pulse velocities in the range $0.002 - 0.05$ m s^{-1}.

1. Introduction

The Upper Drau River, located in Eastern Tyrol (Austria), is an alpine gravel bed river affected by a hydropower plant (built by the Tyrolean Water Power Company TIWAG in 1986), leaving a 24 km long stretch as a residual reach. Many active torrents and tributaries discharge into the Upper Drau River and resupply new sediment to the system. Due to the altered hydrologic condition based on the hydropower operation, the former dynamic sediment equilibrium in the Upper Drau changed into a system with reduced transport capacity compared to the pre-regulated state. As a result, sediment deposition in the residual flow reach intensified, hence increasing maintenance efforts to stabilize this river section and ensure flood protection.

This development led to the introduction of a new sediment management concept for the Upper Drau River in 2001. In addition, a continuous bedload monitoring system was installed (by TIWAG) downstream the residual reach, to improve the knowledge on local bedload dynamics and provide additional information for an enhanced sediment management (Schöberl and Reindl, 2002). The systems uses impact plate geophones, an automated monitoring method that records the impacts made by bedload as it rolls and hops or slides downstream.

Since the intensity of bedload transport is measured indirectly, geophone systems need calibration by direct bedload monitoring to obtain actual bedload fluxes (Rickenmann et al., 2012), usually done using comparative measurements involving direct methods on site. Although progress has been made working out signal characteristics in detail (Krein et al., 2008; Mizuyama, 2010; Rickenmann et al., 2014; Tsakiris et al., 2014; Wyss et al., 2016), no laboratory-based calibration of surrogate bedload monitoring techniques is yet available (Gray et al., 2010; Rickenmann et al., 2014). Even uncalibrated, recent studies (Mao et al., 2014; Downs et al., 2015) pointed out the great potential of surrogate bedload monitoring for detailed analyses of bedload transport fluctuations.

Now, after 15 years of geophone operation on the Upper Drau River, a detailed time series of bedload intensity is available, covering a vast

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number of major and minor storm events that have occurred since then. This time series provides unprecedented insights into the dynamics of sediment storage and bedload transport in a river reach that is affected by hydropower flow management. The continuous, high-resolution surrogate bedload monitoring data in addition with the hydrologic setup of the Upper Drau River, a natural flume, allowed the authors to do a detailed analysis of bedload pulses.

Bedload pulses or bedload waves are distinct temporal variations of bedload transport which occur commonly on many gravel bed rivers even at steady flow conditions (e.g. annual flood). During these fluctuations, measured transport rates can vary by several orders of magnitude for a given water discharge (Gomez, 1983; Reid and Laronne, 1995; Habersack et al., 2008).

Following a classification presented in Nicholas et al. (1995) and Cudden and Hoey (2003), sediment pulses can be distinguished using a scale concept, allowing a better understanding of the mechanisms forming these fluctuations. Micro-scale bedload transport is characterized by the movement of single particles which interact and mobilize adjacent grains. Meso-scale bedload pulses refer to the migration of particle clusters and low-angle bedload sheets and occur at timescales far beyond a single flood event (Gomez, 1983; Iseya and Ikeda, 1987; Nicholas et al., 1995; Recking et al., 2009). Bed load sheets have been shown experimentally to result from interactions between coarse and fine fractions during bed load transport (Dietrich et al., 1989) and its dynamics are controlled mainly by the rate of sediment supply (Nelson et al., 2009). Pulsing behaviour at the macro-scale is argued to be dominated by the migration of gravel bars and erosion-deposition sequences at timescales longer than a single flood event (Gomez et al., 1989). Mega-scale pulses can be explained by the transport of bar compounds and are controlled by local sediment supply (Meade, 1985; Sutherland et al., 2002). Super-scale pulses refer to changes in sediment supply at the basin scale, can persist for decades and trigger major adjustments of the river valley (Gilbert, 1917). The transition between these pulse-scales is not fixed and varies between different river systems (Nicholas et al., 1995) and relatively little is known about their interrelationship (Venditti et al., 2016). Thus, more information concerning their interrelationship based on field data is required.

The downstream propagation of bedload pulses is influenced by translation and dispersion effects which in turn depend on the grain size and input volume of the pulse (Lisle et al., 2001; Sklar et al., 2009). Various studies reveal dispersion to be the dominant effect, and bedload pulses exhibit significant deformation while moving (Cui et al., 2003; Cui and Parker, 2005). Recent reports based on laboratory experiments show intensified pulse translation when bedload pulses are low in amplitude and finer-grained than the bed material (Sklar et al., 2009; Humphries et al., 2012). Both latter studies indicate a tendency for higher bedload pulse celerity with increased pulse volume, decreasing grain size and increased hydraulic stress, although field data are still needed to validate these tendencies.

The main objective of this study is a characterization of observed bedload pulses at the Upper Drau River and the determination of time lags between bedload flux and water discharge. We also asses the influence of these temporal variations on the relationship between water discharge and bedload transport and provide an interpretation of the evolution and origin of the detected bedload pulses. Finally, the current paper demonstrates the advantages of continuous surrogate methods in monitoring bedload transport and its inherent temporal fluctuations.

2. Study site

2.1. The Upper Drau catchment

The Drau River originates in the Toblacher Feld (Southern Tyrol) and flows eastwards through the eastern Puster valley towards Lienz (Eastern Tyrol), where it joins with the larger Isel River. The northern part of the 672 km^2 catchment area upstream the town of Lienz (Fig. 1) consists of paragneiss and quartz phyllite, whereas the southern part is dominated by limestone and dolomite (Schuster et al., 2013). The Upper Drau River is characterized by a nivo-pluvial runoff regime. The snowmelt-period typically starts in mid-April/early May with increasing but moderate water discharge over several weeks. Brief water discharge peaks in summer are typically associated with thunderstorm events. The highest water discharges occasionally occur in autumn due to intensive and long duration rain events that can trigger catastrophic floods such as in 1965 and 1966. The mean discharge at the Falkensteinsteg monitoring station, located 2 km upstream of the confluence with the Isel River, is 13.5 m^3 s^{-1}, the annually flood $Q_1 = 63$ m^3 s^{-1} and the five-year recurrence flood $Q_5 = 116$ m^3 s^{-1}.

Many active torrents and tributaries discharge into the Upper Drau River and deliver new sediment into the system. This stochastically variable local supply leads to a sediment balance, forming a dynamic equilibrium in the pre-regulated era (Schöberl and Reindl, 2002). Multiple discontinuities by several transversal regulation measures (e.g. ramps) performed in the 1970, reduce the capability of the Upper Drau River to smooth its bed gradient.

The most recent major impact on sediment dynamics of the Upper Drau River was the construction of the Strassen-Amlach hydropower plant. Operation began in 1989 and leaves a 24 km long stretch of the Upper Drau River as a residual reach (Fig. 2). The water intake weir at Tassenbach diverts flow from the upper Drau River (catchment area of 422 km^2 at Tassenbach) and routes it to the Tassenbach Reservoir (storage capacity 240,000 m^3), from where a 22 km headrace tunnel leads to the powerhouse in Amlach. Beyond the turbine passage, the processed water flows back to the Drau River. The design flow of the power plant is 20 m^3 s^{-1} with a total drop height of 370 m, resulting in an annual production capacity of 219 GWh (TIWAG, 1989).

The arithmetic mean grain sizes d_m in the Upper Drau River range from 15–40 mm with a d_{max} of 100–200 mm, respectively 18–43 mm in the tributaries (Fig. 2d). The river morphology in the residual reach is mainly stretched with a width of about 20 m (Fig. 2c). In the area of river widening (Thal, Leisach), braided reaches are interspersed with channel width as large as 50–100 m. The stream gradient of the lower residual reach (Fig. 3) displays an average gradient of 1.1% and range from 0.6% to 2.3%. The development of the residual reach was analysed by Habersack et al. (2000) and in a comprehensive study by Schöberl and Reindl (2002). Due to the reduced transport capacity, local deposition of bedload occurs in the residual flow reach, especially in river widenings, forming a bedload source during flood events. There, an increasing vegetation cover is influencing the bedload dynamics. As a

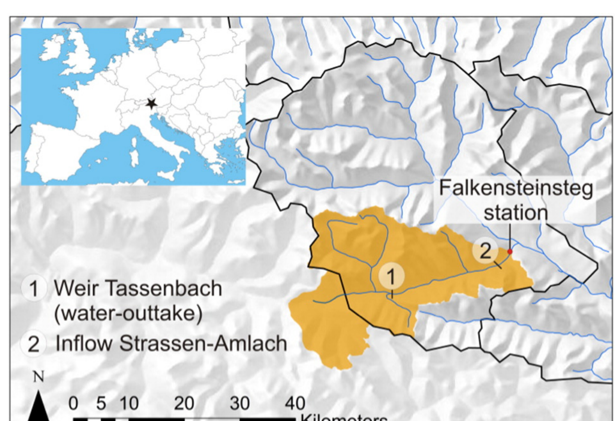

Fig. 1. Catchment area of the Upper Drau River with the location of the Falkensteinsteg monitoring station (red dot), the Tassenbach weir (1) and the inflow of the Strassen-Amlach hydropower plant (2), modified from BMLFUW (2007). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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