Geomorphology 291 (2017) 57–68

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Analysis and classification of bedload transport events with variable process characteristics

Andrea Kreisler [a,*], Markus Moser [b], Johann Aigner [a], Rolf Rindler [a], Michael Tritthart [a], Helmut Habersack [a]

[a] University of Natural Resources and Life Sciences, Vienna, Muthgasse 107, 1190 Vienna, Austria
[b] Austrian Service for Torrent and Avalanche Control, Johann Löcker Straße 3, 5580 Tamsweg, Austria

ARTICLE INFO

Article history:
Received 5 January 2016
Received in revised form 23 June 2016
Accepted 23 June 2016
Available online 25 June 2016

Keywords:
Integrative bedload monitoring system
Bedload transport events
Transport efficiency
Process types

ABSTRACT

Knowledge about the magnitude of bedload fluxes at given hydraulic conditions in natural streams is essential for improved process understanding, for the application, calibration and validation of bedload transport formulas, and for numerical sediment transport models. Nonetheless, extensive field measurements of bedload transport are challenging and therefore data from such efforts are rare.

Bedload transport has been measured comprehensively at the downstream section of the Urslau torrent in Salzburg, Austria, since 2011. We used an integrative monitoring system that combines direct (mobile basket sampler, slot sampler) and indirect measuring devices (geophone plates). Continuous information about the intensity and distribution of bedload transport within the channel cross-section is available in high spatial and temporal resolution. Seven geophone plates at a stream width of 8 m are part of a measurement system that delivers data in 1-min intervals. These geophone data are calibrated using results of direct bedload measurements, providing an opportunity to calculate bedload rates and bedload yields in selected time periods.

Continuous data on the bedload transport process over three years enabled assessing several bedload transport events. The investigation of bedload transport rate/discharge relationships reveals order-of-magnitude changes. For individual events, we observed shifts in the data, reflecting different bedload rates at comparable hydraulic conditions. This study reveals that variable sediment supply conditions affect the prevailing bedload transport rates at the Urslau stream. Calculating the bedload transport efficiency enables comparing bedload transport events that exhibit similar process characteristics. Finally, we provide a conceptual model of bedload transport process types as a function of bedload transport efficiency and dimensionless stream power.

1. Introduction

Field measurements of bedload transport processes, which reveal bedload fluxes at given hydraulic conditions, deliver data fundamental to river engineering works. They also form the basis for applying and calibrating bedload transport formulas as well as for morphodynamic models (Tritthart et al., 2011). In natural streams, many researchers have observed a high temporal and spatial variability of bedload transport processes and experienced a wide scatter of bedload transport rates for given hydraulic conditions (Vericat and Batalla, 2006, Habersack et al., 2008, Turowski and Rickenmann, 2009, Lucía et al., 2013, Dell'Agnese et al., 2014, Mao et al., 2014).

Bedload transport rates and bedload yields of single flood events in mountain streams are determined by several factors. One factor is the transport capacity of a stream, which is defined as the maximum tractive sediment load that is transported for given hydraulic and sedimentary conditions (Gray and Simões, 2008). Another factor is variation in sediments available for bedload transport (Gintz et al., 1996, Benda and Dunne, 1997, Lenzi et al., 2004, Turowski et al., 2009). The sediment supply of a stream comprises (i) in-channel sediment sources, generated through riverbed or bank erosion, armour break-up, bar mobilisation, (ii) influxes of tributaries, and (iii) sediments from hillslope processes. The latter, due to their episodic nature, variably influence the sediment supply for the channel (Benda and Dunne, 1997).

Sediment supply interacts with channel morphology, bed stability and sediment transport processes at various scales (Church et al., 1998, Buffington and Montgomery, 1999, Habersack, 2000) and influences the development of bedform features in alluvial rivers (Schumm, 1985, Venditti et al., 2012, Zunka et al., 2015). Bed stabilizing structures, such as imbricated stones, stone clusters, stone lines and stone cells develop during periods of low sediment supply (Church et al., 1998; Hassan and Church, 2000). Lack of sediment supply leads to the development of a static (or stable, as denoted in Gomez, 1994)

* Corresponding author.
E-mail address: andrea.kreisler@boku.ac.at (A. Kreisler).

http://dx.doi.org/10.1016/j.geomorph.2016.06.033

armour layer, preventing river bed erosion (Dietrich et al., 1989, Parker and Sutherland, 1990). In flume experiments, for example, reducing the sediment input expanded the coarse and inactive zones on the channel bed (Dietrich et al., 1989). In contrast, a mobile armour layer develops upon significant sediment supply from upstream (Parker and Klingeman, 1982, Hunziker and Jaeggi, 2002). Sediment supply conditions further determine the distribution of patches (Nelson et al., 2009) that occur as migrating bedload sheets ("free patches") or as relatively "stable patches". Patches are accumulations of homogeneous fine bed material and arise from shear stress divergences that are forced by bar morphology and flow obstructions of immobile large boulders (Laronne et al., 2001). They form an important bedload source during small and medium bedload transport events (Garcia et al., 2000, Vericat et al., 2008). Flume experiments showed a strong variability in sediment discharge when bedload sheets were transported: bedload-sheet migration rates decreased as sediment supply was reduced, and completely disappeared with no sediment input (Nelson et al., 2009). On a larger scale, sediment inputs from hillslope activities and mass movements can strongly influence sediment transport and may lead to channel reconfigurations (Lenzi et al., 2004). Variations in sediment supply caused by major flood events and mud flows can change transported bedload rates at comparable flow conditions (Lenzi et al., 2004, Turowski et al., 2009). In a tracer study, Gintz et al. (1996) demonstrated that the average distances travelled by sediments increased after an exceptional event, when sediment input increased and channel configurations changed.

Clearly, the determination of sediment supply conditions is essential for sediment management. Although approaches to assess the sediment supply in a reach are available (Yager et al., 2012), this parameter remains difficult to determine (Bravo-Espinosa et al., 2003, Yager et al., 2012). Several studies calculated sediment availability by dividing measured bedload transport rates by hydraulic parameters (Lenzi et al., 2004, Yager et al., 2012, Recking, 2012, Rickenmann et al., 2012). Determining sediment availability therefore requires comprehensive bedload monitoring results. Nonetheless, such data are rarely available because bedload transport processes are difficult to measure due their complexity and monitoring work is often expensive and challenging.

Direct and indirect monitoring methods can be used to assess these processes (Habersack et al., 2010). Indirect measuring devices enable continuous and automated measurement of bedload transport activity over time and across the entire stream cross-section. Indirect bedload monitoring sensors, including plate geophones (Habersack et al., 2010, Rickenmann et al., 2013) and Japanese pipe hydrophones (Mizuyama et al., 2010a, Mizuyama et al., 2010b), are widely used and yield valuable data. Field calibration of indirect measurement methods using direct measuring devices is required in order to properly apply these instruments (Gray et al., 2010). Direct measurement devices include retention basins, which are surveyed in regular intervals (Rickenmann et al., 2012) or continuously (Lenzi et al., 1999), portable basket samplers (Helley and Smith, 1971, Emmett, 1980, Bunte et al., 2004) and fixed slot samplers (Reid et al., 1980, Garcia et al., 2000, Habersack et al., 2001, Laronne et al., 2003, Vericat and Batalla, 2010, Lucía et al., 2013). Basket samplers and slot samplers help determine (specific) bedload transport rates and sediment grain size distributions. Habersack et al. (2016) present the integrative monitoring system, which combines indirect and direct monitoring methods, and specify its possibilities and restrictions. They conclude that applying this integrative system provides comprehensive data on the transport process.

This study presents the integrative bedload monitoring station at the downstream section of the Urslau stream, where geophones and direct monitoring devices are combined. Continuous information about the intensity and distribution of bedload transport within the channel cross-section in high spatial and temporal resolution is available. We present monitoring results of the Urslau stream over three years and analyse various bedload transport events. A wide scatter of bedload transport rates for similar flow rates occurred at the measuring site. We hypothesize that variable sediment mobility can explain changes in the magnitudes of the bedload transport rate/discharge relationships here. The bedload transport efficiency – basically the relation between prevailing bedload transport rates and discharge – reveals a wide range of values for individual events. This enabled us to group bedload transport events exhibiting similar process characteristics. Finally, we present a conceptual model to categorize bedload transport events as a function of bedload transport efficiency and dimensionless stream power.

2. Study site

The Urslau catchment is located in the province of Salzburg in the alpine region of Austria (Fig. 1) and encompasses 122 km^2.

The catchment is characterised by two geologically different zones: the Greywacke Zone in the southern part, where sand-, silt- and claystone, phyllite and micaschist dominate, and the Northern Limestone Alps in the northern part, featuring dolomite and carbonate rocks. The Greywacke Zone is characterised by a smooth landscape, rich in meadows. High mountain ranges are typical for the Northern Limestones Alps. The elevations within the Urslau catchment range between 716 and 2840 m a.s.l. Total mean annual precipitation is 1611.2 mm (1961–1990) (Kling et al., 2007), whereby 59.8% falls from April to September (Skoda et al., 2007).

Fig. 2a provides an overview of the Urslau catchment. The Urslau stream originates in the Northern Limestone Alps at an elevation of approximately 1800 m a.s.l. and discharges after a total flow length of 21.3 km into the Saalach River (716 m a.s.l.). The average channel slope is 5%. The gradient of the Urslau channel exhibits a steep concave longitudinal profile. The upper reach (distance to Saalach River 21.3–19.1 km) features a steep channel gradient (27%). The slope decreases within the middle reach to 8.4% (distance to Saalach 19.1–17 km) and further to 2.8% (distance to Saalach 17 km to 10.1 km). The mean slope gradient of the lower reach (10.1 km to the junction to Saalach) is 1.1%.

Downstream of the steep upper section (Fig. 2b and Fig. 3a) the stream passes over extensive alluvial deposits (Fig. 2c and Fig. 3a). The widths of these unvegetated alluvial deposits vary between 20 and 40 m. Seventeen kilometers upstream of the Saalach junction, the Urslau represents a partially confined, straight, single thread alluvial channel (Fig. 3b,c). Stream width varies from 7 to 10 m and the mean bed slope gradient is 2.8%. A plane bed type (Montgomery and Buffington, 1997) characterizes the reach. The Urslau also exhibits scattered mobile mid-channel and alternate bars. Bank erosion has been observed throughout the channel. The river bed features protruding cobbles and boulders. Patches of finer material occur in the wakes of protruding cobbles.

The surface material of the stream bed is unsorted and has a wide grain size distribution (see D_{50} values in Fig. 2a). At the bedload monitoring station, D_{50} of the surface is 0.034 m and D_{50} of the subsurface is 0.024 m, resulting in a degree of armouring (D_{50} surface/D_{50} subsurface = 1.4).

Three important tributaries (Pirnbach: Fig. 2d; Handlergraben: Fig. 2e; and Schwarzbach: Fig. 2f) enter the mid-reach of the Urslau. All feature a high potential sediment supply due to erosion and hillslope activities (Neumayr, 2004).

At the mid reach, at 830 m a.s.l. and approximately 10 km upstream of the Saalach-junction, a bedload monitoring station was installed in 2011 (Fig. 3d). The catchment size upstream of this station is 56 km^2. The mean slope of the stream in the section 150 m upstream of the station is 1.8%. Channel width at the measuring site is 8 m.

A stream gauging station – operated by the hydrographic survey of Salzburg since 2011 – is located 25 m upstream of the bedload monitoring station. It is equipped with a hydrostatic pressure sensor and surface radar. The hydrographic survey performs discharge measurements and provides water flow data in 15-min intervals. A second gauging station