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High resolution quantification of slope–channel coupling in an alpine geosystem

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Abstract Fluvial sediment transport in alpine rivers is strongly connected to available sediment which comes from slope source areas (talus and debris cones). Consequently, the quantification of slope–channel coupling in terms of sediment supply to the river is a major task for fluvial sediment budget studies. Sometimes, the more interesting and useful study sites are located in dangerous areas and field work is difficult, if not impossible. Due to the emerging technology of laser-scanning (both terrestrial and airborne) it is now possible to obtain high resolution earth surface data for use in sediment budget studies. The Reintal Valley (Bavarian Alps) is a natural high-mountain laboratory where sediment transport processes and slope–channel coupling can be studied in detail. Due to a 2005 dam-break flood, the river system is in a state of disequilibrium, making it an exceptional study site for investigating these processes. The sediment flux from the sources to the river channel was quantified by using the innovative terrestrial laser-scanning (TLS) methodology. During the 2008 field season the sediment sources fed the Partnach River with more than 2600 t of sediment. Only a minor part was transported as bed load. Most of the coarse sediment was stored on the channel bed, a finding which was evaluated by concurrent bed load measurements at the outlet of the catchment. The sediment stored on the river bed was re-worked by 2009 snow melt floods and transported further downstream.

Key words slope–channel coupling; terrestrial laser-scanning; DEM; sediment sources; sediment budget; bed load; sediment transport; Partnach River; Reintal

INTRODUCTION

The concept of geomorphic coupling or connectivity has gained a growing importance over the last few decades in studies of sediment transport dynamics (Caine & Swanson, 1989; Hooke, 2003; Korup, 2005; Fryirs *et al.*, 2007). Several schemes were developed for characterizing different types of slope–channel coupling (Korup, 2005) or channel system connectivity (Hooke, 2003) in terms of sediment transfer, but generally only in a qualitative way. For sediment budgets studies it is important to get quantitative measures of spatial and temporal sediment dislocation expressed as surface changes (erosion, storage, accumulation) of sediment stores (e.g. Warburton, 1990). As yet, studies of sediment budgets in high mountain geosystems are rare and the spatial resolution has been restricted to a few metres or more, based on the available data sets (airphotos, digital elevation models) or measuring devices (theodolites, GPS). Using the innovative terrestrial laser-scanning (TLS) technology it is possible to detect surface changes at a very high resolution, up to a few centimetres (Heritage & Hetherington, 2007).

In our study we combine the sediment budget approach and the TLS technology in order to obtain quantitative information on slope–channel coupling in an alpine geosystem. The main aim of this study is the quantification of the sediment input to a fluvial system in a high-mountain environment for the 2008 observation period. The main focus is on the TLS of the sediment source areas and their surface changes as a quantitative measure for slope–channel coupling in a known time interval. In a second step, we compare the measured sediment input to the river with the results of bed load measurements published in a companion paper by Morche & Bryk (2010) and present an unbalanced sediment budget.

STUDY AREA

The Reintal Valley is a U-shaped valley located in the northern limestone Alps (Wettersteingebirge) in Bavaria (Fig. 1). The Partnach River at the Bockhuette gauging station drains a 27 km^2 catchment below Mount Zugspitze and joins the Loisach River in Garmisch-

Partenkirchen, 80 km south of Munich (Morche *et al.*, 2008a). Large landslides dammed the Partnach River in the Reintal Valley creating two small lakes and dividing the valley into multiple sub-catchments (Morche *et al.*, 2006; Sass *et al.*, 2007). On 22–23 August 2005, more than 50 000 m^3 of sediment was mobilized after the lowermost landslide dam at the lake "Vordere Blaue Gumpe" (VBG) failed during a storm (Morche *et al.*, 2007). Due to the dambreak flood, large erosion scars on several talus cones were created on the slopes (Morche *et al.*, 2008b). Thus the sediment stores and the whole alluvial plain of the VBG are now coupled with the Partnach River in terms of sediment transfers.

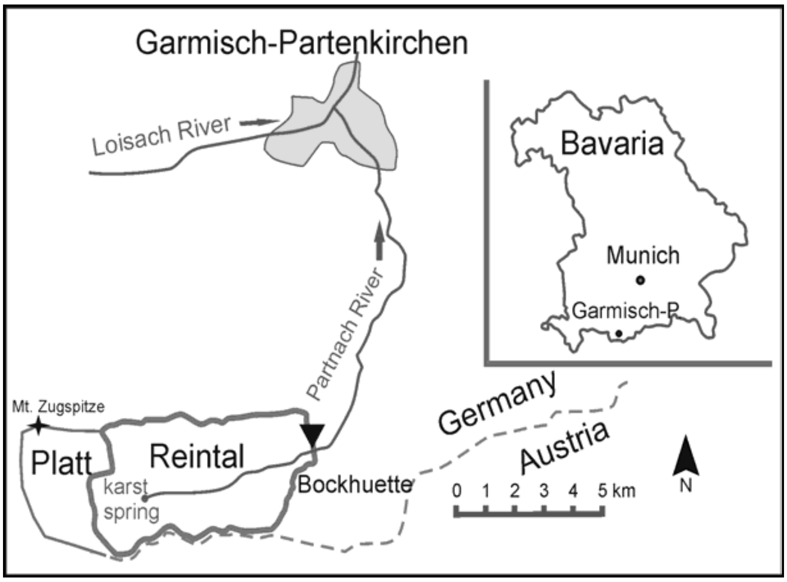

Fig. 1 Location of the Reintal Valley in the Wetterstein Mountains below the peak Zugspitze (2962 m), Germany. The black triangle shows the location of the Bockhuette gauging station at the outlet of the catchment.

Table 1 Characteristics of the sediment sources (VBG = Vordere Blaue Gumpe, VBG/TC = talus cone at the VBG, TC = talus cone) and their scans. The contact line, the length of active slope–channel coupling, was mapped using orthophotos from 2003 and 2006, see Fig. 2. Volume changes include an error of ±5 mm according to Morche *et al.* (2008b).

	VBG	VBG/TC	TC
Contact line 2003 (total 137 m) (m)	0 (dam present)	71	51
Contact line 2006 (total 605 m) (m)	108	150	75
Scan 1, date and number of single scans	23.06.2008 (3)	10.07.2008 (5)	24.06.2008 (4)
Scan 2, date and number of single scans	30.09.2008 (4)	19.08.2008 (5)	18.08.2008 (3)
Points for comparison of scan 1 and 2	2816526	4568333	1146402
Volume change (m^3)	–438	–675	–227

METHODS

Mapping of sediment source areas

All sediment sources and sinks were mapped using high resolution orthophotos from 2003 (pre-dambreak) and 2006 (post-dambreak) (Fig. 2). Active sediment bodies are fresh forms with no weathering rinds while the inactive bodies have signs of weathering. To measure slope–channel coupling, the lines of direct contact between the slopes and the channel system (e.g. undercut banks, erosion scars on talus cones) were digitized for 2003 and 2006 in the studied channel reach (VBG to the Bockhuette gauging station at the end of the basin). The contact line between slopes

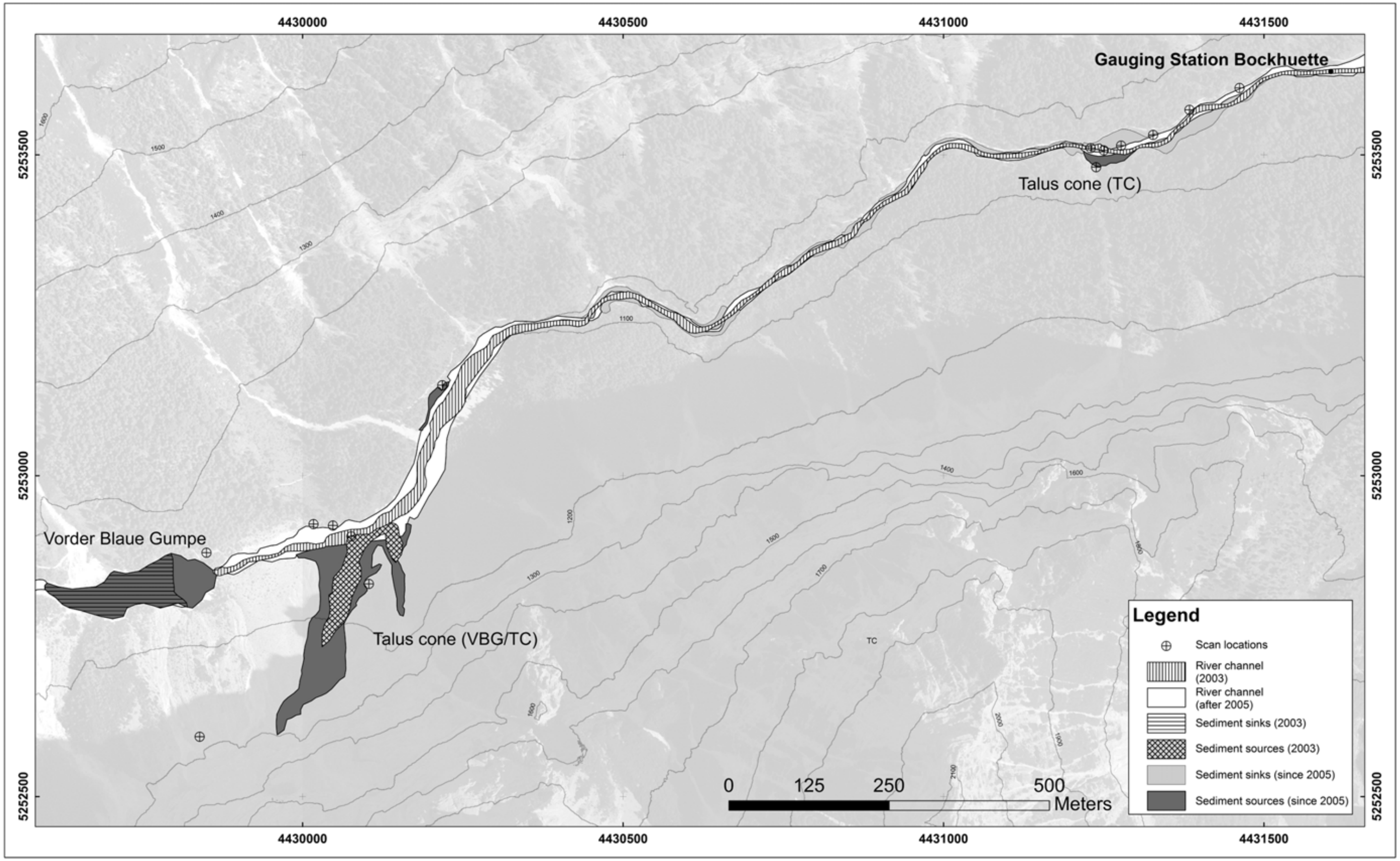

Fig. 2. Large scale map of the entire study area with the investigated sediment sources in 2008; VBG = Vordere Blaue Gumpe, VBG/TC = talus cone at the VBG, TC= talus cone. Flow direction of the Partnach River is from left to right. Background orthophoto was taken on 18 July 2006 (© Landesamt für Vermessung und Geoinformation, permission to use and publication from 6 February 2007, reference number: VM3831B-oN/7-0138.)

and channel is equal to the length of the channel bank on both sides of the channel. In total, the length of direct contact increased from a length of 137 m in 2003 to 605 m in 2006. The value for 2008 was supported by field observations. In a next step, the most prominent sediment sources were chosen for the TLS monitoring programme (Table 1).

Terrestrial laser-scanning

Field work During the 2008 field season, an OPTECH ILRIS-3_6D terrestrial laser scanner was used for collecting the raw data. This TLS-system has a two-axis beam-scanning mechanism with a pulsed time-of-flight laser range finder to measure 3-D positions in the field within a range from 3 m to 1500 m. The accuracy at a distance of 100 m is <10 mm. By using the PanTilt option it is possible to scan a panorama in 360 degrees. Without a panorama function, it is recommended to scan from as many locations as possible. However, using the PanTilt option it is possible to scan from two or three locations only. There are several issues associated with performing an optimal scan that need to be considered. One problem is vegetation, either within or infront of the surveyed object. Every tree creates a shadow where data are not available. Another potential problem is that parts within an area chosen for scanning might not be reached by the laser beam. No reliable data were obtained for areas behind obstacles. Shadows appear in the point cloud (scatter diagram of measured points). Several scan positions may be necessary to avoid this problem.

Before starting the scan, the average distance to the target has to be determined manually or automatically. Based on the nature of the surveyed target, the spacing of scan points is the most important variable for quality and size of the point cloud. The spacing value is proposed by the measuring device. It shows the resolution at the average target distance. Depending on the average distance, the spacing value has to be adjusted. For a distance of 100 m a spacing of 20 is equal to a resolution of 20 mm. With higher spacing, a lower scan time with lower resolution can be reached, while a lower spacing value increases the scan time and the resolution. The absolute scan time is restricted by the energy status and depends on weather conditions. The battery cells lasts longer under dry and warm weather.

During the 2008 field season, 24 single scans were performed on 10 field days with scan times ranging from 10 to 60 minutes. The average spatial resolution was about 31.5 mm. For every sediment source area, multiple scans with substantial overlap were carried out. Individual scans contained between 1 and 3 million points, depending on the chosen resolution. The collected data for all scans have an overall volume of 4 GB.

Data analysis By using the Parser tool, the raw data collected in the field were converted to a usable file format for further analysis. Thereafter, we applied the software package PolyWorks and its special tools for detailed data analysis (InnovMetric Software, 2008). All single scans were aligned together to one single point cloud for each sediment source. At least three manually selected reference points between two scans were used. Then PolyWorks matched together the scans automatically in order to minimize the standard deviation between the two compared surfaces. This procedure can be done either in the IMAlign or IMInspect software tool. A function to reduce the overlap area and to reduce the point number was used to optimize the point clouds according to the software guidelines (InnovMetric Software, 2008).

In the next step, the complete point clouds, containing several million single points (Table 1), were imported into IMInspect. All further calculations were carried out in this software tool. A triangulated network (TIN) of each surface was created from the point cloud as a basis for the calculation of the volume changes. In the PolyWorks software it is not possible to directly calculate the volume difference between two surfaces (e.g. TINs for two different scans). In this situation, an artificial third surface (normally a plane) is created and each TIN is subtracted/added from/to this plane. Finally, the volume values are subtracted from each other and the total volume change between the two TINs (i.e. time steps) is calculated. It is also possible to show where the changes occurred using a function in PolyWorks to compare two point clouds or surfaces. In Fig. 3, a comparison of the talus cone near the Bockhuette gauging station shows that there are several areas within the talus cone with sediment erosion and also sediment accumulation.

Discharge The Bockhuette gauging station is located at the outlet of the Reintal valley (Fig. 1) and is equipped with a sensor for water level and a data logger that records temperature, electrical conductivity and turbidity every 15 minutes. For various stream stages, discharge was measured during the 2008 field season and a relationship between stage and discharge was established by Morche & Bryk (2010).

RESULTS

Vordere Blaue Gumpe (VBG) At this location, on 23 June the first three scans were performed with about 20 million points, and on 30 September the last four scans were undertaken with 14 million points. At this location the scanning distance is about 250 m from the top of the southern talus cone (Fig. 2). Based on a comparison of both scans, a volume change of 438 m^3 was determined.

Talus cone at the Vordere Blaue Gumpe (VBG/TC) The largest volume change, of 675 m^3, was measured at the large talus cone (VBG/TC) east of the VBG (Fig. 2). This talus cone supplied the most sediment ito the Partnach River in 2008. For a complete observation of this location, five scans were carried out on 10 July. These scans were merged to a point cloud of about 20 million points. The talus cone was scanned from three different locations with distances ranging from 75 to 250 m. On 30 September the object was scanned from the same scan locations as in July, with a lower resolution to get a smaller point cloud with only 15 million points.

Talus cone (TC) A talus cone (TC) located further downstream (Fig. 2) was scanned in four single scans on 29 June and three scans on 18 August. Because of its size and the small distance to the scan location (30 m), it was possible to get the highest resolution of about 20 mm spacing

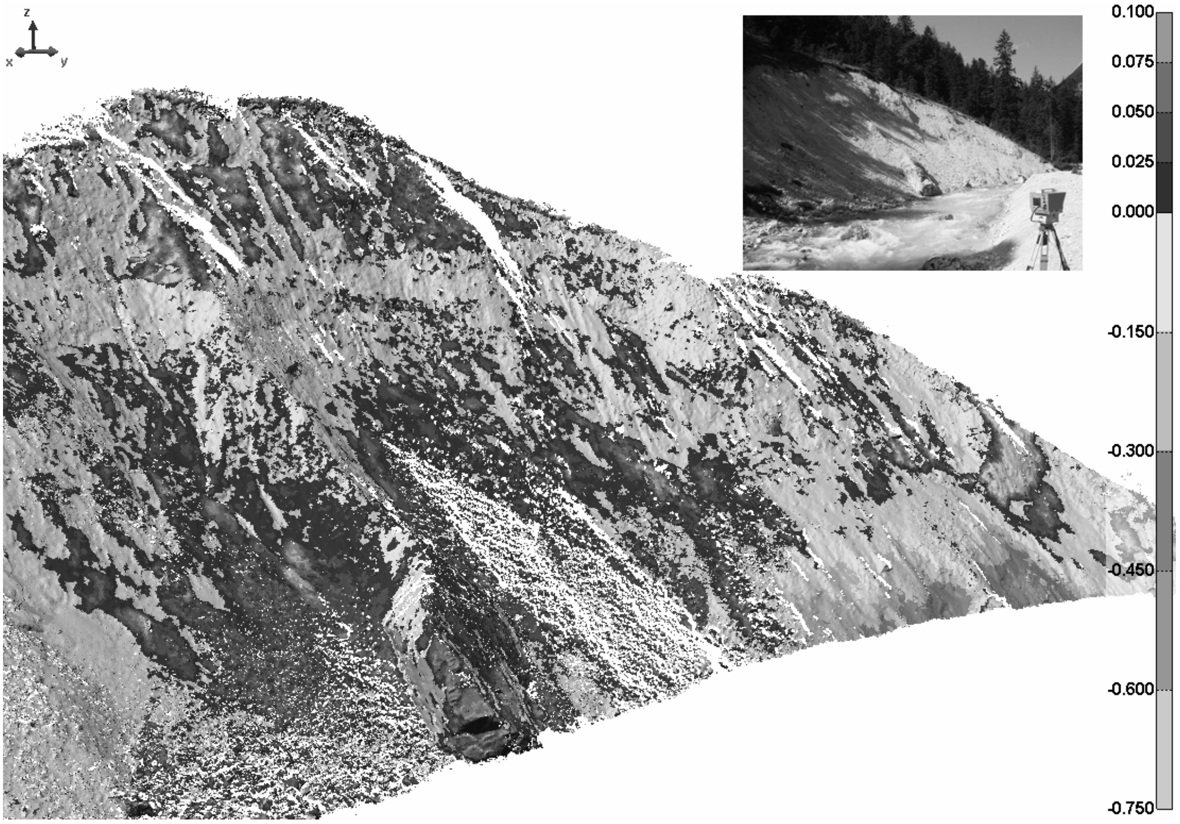

Fig. 3 The large scar of a talus cone (TC) shown in an accumulation and erosion balance figure and a small photo. Black colours represent accumulation up to 5 cm from June to September 2008 and grey colours represent eroded areas on the talus cone scar in 10 cm steps.

between the points. After merging all single scans, both point clouds contained between 5 and 9 million points. The change in volume was estimated at 227 m^3.

For a detailed analysis of the spatial pattern of areas where erosion and accumulation occurred, a difference figure between the two scans was created. As an example, the result of this calculation for TC is shown in Fig. 3. The legend on the right side represents change within the talus cone: values are positive for accumulation and negative for erosion (values are displayed in several grey shades). A maximum erosion of 50 cm was detected. A region with eroded material on the upside and accumulated material on the downside shows that reworking of sediment occurred within a small region. It is possible that a volume change was detected, but no material was transferred into the river. PolyWorks also creates reports for all actions. In these reports some statistical parameters such as arithmetic mean and standard deviation were summarized. These parameters show the size of the error which may occur during the registration and the comparison of the two scans.

Sediment input There was a total decrease in volume of 1340 m^3 on the three sediment source areas (Table 1). The sediment input to the Partnach River between June and September 2008 was calculated to be about 2680 t using an assumed bulk density of 2 t m^{-3} for unconsolidated limestone.

Hydrograph, bed load transport and sediment budget By using the water level data and the stage–discharge rating curve, a hydrograph was created (Fig. 4). The peak discharge of about 8.4 m^3 s^{-1} occurred in June and a second flood (8 m^3 s^{-1}) in August 2008. While the discharge is reduced in winter, the lowest discharges were recorded in April (0.57 m^3 s^{-1}) before snowmelt, and at the end of the observation period in November. For 2008 the mean discharge was 2.24 m^3 s^{-1} during the 206 days of observation. Bed load and discharge measurements were taken at different water stages by Morche & Bryk (2010). They used a Helley-Smith sampler to measure bed load on 22 occasions. The critical discharge threshold for bed load transport in the Partnach River was 1 m^3 s^{-1} in 2008 (Fig. 4). A rating curve for discharge and unit bed load was established. The total sediment exported as bed load during 2008 was calculated using the hydrograph (Fig. 4), the values of channel width containing bed load transport in the measured profile, and the rating curve.

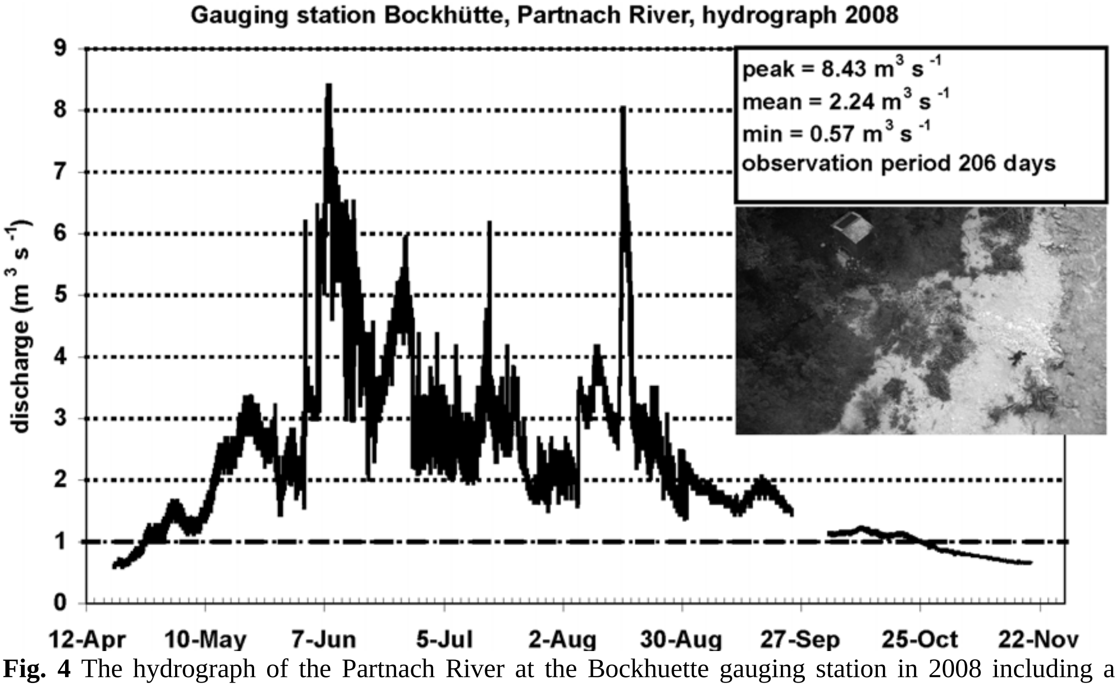

Fig. 4 The hydrograph of the Partnach River at the Bockhuette gauging station in 2008 including a photograph of the area around the station taken by a microdrone. The interruption in the hydrograph in September 2008 was caused by a malfunction in the data logger. The bold dashed line indicates the discharge threshold for bed load transport starting at >1 m^3 s^{-1}.

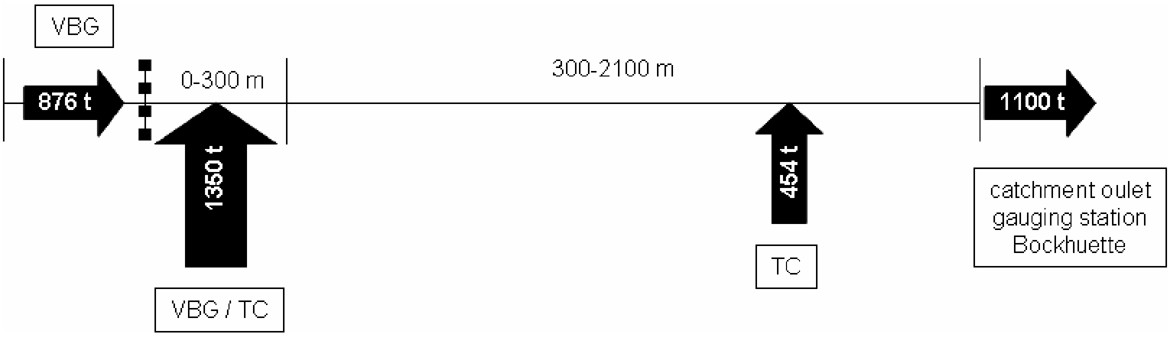

Fig. 5 Unbalanced sediment budget of the Partnach River between Vordere Blaue Gumpe (VBG) and Bockhuette (June–September 2008). 2680 t of input and 1100 t of export indicate a net storage of 1580 t on the river bed.

About 2270 t of sediment were exported out of the valley during the 2008 field season (Morche & Bryk, 2010). Between June and September 2008 there was an input of sediment of about 2680 t measured with TLS (see above). A net export of 1100 t was measured at the outlet. Taking the difference between sediment input and sediment output, we assume that there was a net storage of 1580 t of sediment (Fig. 5). Due to the low discharge of $<1\ m^3\ s^{-1}$ before March/April and after September, no additional bed load samples were collected during these periods. Suspended sediment flux was not investigated in 2008 as a previous study showed that suspended sediments were of minor importance in the total load of the Partnach River (Schmidt & Morche, 2006).

Further field observations have shown that no fresh deposits on the banks of the Partnach River were created in 2008, a fact that confirms the storage function of the riverbed. As discussed by Morche & Bryk (2010), the in-stream sediment stores on the river bed were emptied and removed by the first snowmelt floods in 2009. The time lag of one year in stream sediment storage was observed in the 2003/2004 season for the Partnach River, when a debris flow fed the channel with sediment and increased bed load was measured one year later (Morche *et al.*, 2008a).

CONCLUSIONS

Based on detailed mapping we have shown in this study that quantitative measurements of slope–channel coupling are possible. Knowing the amount of sediment transferred from the slope to the channel system in different years it is possible to discriminate between higher and lower coupled periods. On a higher scale we can describe the different sediment sources and their role in the annual bed load transport behaviour of the Partnach River as well as their degree of coupling with the river system. Sediment input values show that in 2008 the large talus cone at the Vordere Blaue Gumpe (VBG/TC) is better coupled to the Partnach River than the VBG itself or the smaller downstream talus cone (TC) (see above). This probably reflects the fact that the large talus cone at the VBG has shown very high morphodynamic activity over the last approx. 200 years (Heckmann *et al.*, 2008). TC/VBG is connected directly to the hydrological catchment of the upslope free-face (Heckmann *et al.*, 2008). Further downslope, fluvial processes and debris flows have dissected the cone several times (Schrott *et al.*, 2006; Heckmann *et al.*, 2008). After the dambreak flood in August 2005 a deep gully-like channel has developed which now serves as a conveyor for the slope sediments.

The VBG is not part of the slope system. It is an alluvial plain and does not get any fluvial sediment input from upstream Partnach River sources due to the damming effects of a large rockslide on the valley bottom (Morche *et al.*, 2006).

The investigations on the sediment source areas and the bed load measurements will be continued in an ongoing research project in order to get medium-term data on the channel response to the dambreak flood. We will continue the established monitoring programme using TLS and add analyses of large scale microdrone air photos (see inset photograph in Fig. 4).

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