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Investigating Channel Response to a Dambreak Flood Event in an Alpine River—Downstream Trends in Stream Power and Channel Bed Particle Characteristics

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Abstract

Fieldwork within the framework of SEDAG (SEDiment cascades in Alpine Geosystems) has focused on hydrology, fluvial sediment transport dynamics, and hydrogeomorphological characteristics of the alpine river Partnach (Reintal Valley, Bavarian Alps, Germany). In August 2005 a dambreak flood occurred in the Reintal Valley. The contributing catchment area supplying material for bed load transport at the outlet of the catchment has been enlarged by more than 33% (4.3 km^2 + 1.6 km^2) due to lake infilling, and thus, reconnecting formerly disconnected parts of the catchment. Post-dambreak downstream variation of total and specific stream power, bed shear stress, and particle characteristics (size and shape) were determined and compared with pre-dambreak findings. As to our knowledge, results of pre- and post-dambreak fluvial-geomorphic investigations have not been published so far for an individual river. Results show high values for total and specific stream power in the post-dambreak regime. In addition, general trends for downstream decreasing in particle size, stream power, and bed shear stress show a degree of regularity after disturbance. Nevertheless, further adjustments of the Partnach channel system in response to the dambreak event are expected in the near future.

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Introduction

In high-altitude fluvial systems large amounts of sediment are transported in the main stream. Also, in high mountain areas landslides very often occur. When they reach the valley bottom channel avulsions occur (Korup, 2004) or even dams are created. If mountain valleys are affected by landslide dams, throughput of the fluvial sediment is interrupted, the valley is fragmented into subsystems, and the landscape is in a state of disturbance (Hewitt, 2006). In this context, Hewitt (2006) described a landslide interruption epicycle of mountain valleys, which consists of five phases:

- Phase 1: the rock avalanche complex—landslide emplacement,
- Phase 2: the impoundment complex—aggradation and constructional landforms upstream of barrier, possible downstream erosion and/or sedimentation,
- Phase 3: the degrading interruption complex—trenching and removal of the impoundment complex, downstream sedimentation,
- Phase 4: the superimposed interruption complex—exhumation of buried valley fill and incision into pre-landslide valley floor,
- Phase 5: the "shadow" interruption complex—minor, persistent legacies of interruption, mainly bedrock forms.

The systems change from Phase 2 to 3 contains the dambreak event that drives new disturbance, if for example the dam was persistent for decades or centuries and the river system adjusted to it.

Also, moraines that dam proglacial lakes or earthen dams have a potential to fail (Costa, 1988). The collapse of dams causes a very rapid conversion of potential to kinetic energy in a flood wave that may have hazardous as well as geomorphic consequences for the downstream channel reaches (Jarrett and Costa, 1986; Vuichard and Zimmermann, 1987; Costa, 1988; Walder and Costa, 1996; Hubbard et al., 2005; Morche et al., 2007). Due to global warming and glacier retreat, the frequency of catastrophic drainage events of moraine-dammed lakes may increase (Desloges and Church, 1992; Clague and Evans, 2000). So the importance of recent studies on the geomorphic impact of dambreak floods increases as well.

The main interesting geomorphic problems of the post-dambreak state are the behavior of fluvial sediment transport, particularly bed-load transport, along with the stream channel response to the new conditions in terms of channel morphology and bed sediment characteristics. Studies concerning these issues are rare due to low frequency of dambreak events. Pitlick (1993) and Bathurst and Ashiq (1998) presented results about the response of the Roaring River channel to the Lawn Lake dambreak flood of 1982. However, to our knowledge, no study has been published which combines results from pre- and post-dambreak investigations. One main problem of studies dealing with the geomorphic effects of large floods is "the quantitative assessment of the effects of the flood: a record of the pre-flood landscape is ideally required, in addition to the monitoring of changes during the passage of the floods and their subsequent modification" (Anderson and Calver, 1977, p. 253). Fortunately, we are able to present such data, and this paper focuses on results of post-dambreak investigations on downstream variation of stream gradient and bed material grain size and shape characteristics of an alpine stream. These new data will be compared with published results from pre-dambreak investigations. Finally, we are able to demonstrate the effect of the dambreak event on the specific stream power at bank-full stage in each channel cross section.

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TABLE 1

Reintal Valley publications with contributions by SEDAG project members.

Schrott et al. (2002)	Sediment storage, geomorphic coupling, temporal variability
Keller and Moser (2002)	Gravitational mass movements, rock fall, soil slip
Hoffmann and Schrott (2002)	Sediment thickness, rockwall retreat rates, 2D-seismic refraction
Heckmann et al. (2002)	Sediment transport, avalanches, sediment yield
Unbenannt (2002)	Fluvial sediment transport, solid load, dissolved load, rating curves
Schrott et al. (2003)	Sediment volume, geomorphometric analysis, seismic refraction
Morche and Schmidt (2005)	Particle size analyses, particle shape analyses, sediment sources/sinks
Heckmann et al. (2005)	Sediment transport, avalanches, disposition model
Becht et al. (2005)	Debris flow, fluvial erosion, sediment budget, sediment cascade
Schrott et al. (2006)	Sediment transfer, sediment storage, alpine sediment cascades
Schneevoigt and Schrott (2006)	Geomorphic systems theory, remote sensing, object-oriented classification, sediment cascade
Schmidt and Morche (2006)	Sediment transport, rating curve techniques, effective discharge
Morche et al. (2006)	Bed load, geodetic surveying, fluvial sediment transport, lake sedimentation
Morche (2006)	Chemical denudation, high mountain hydrology, hydrograph separation
Heckmann (2006)	Avalanches, sediment yield, geomorphic modeling
Sass et al. (2007)	Alluvial plain, rockfall, sedimentation rate, ground-penetrating radar
Sass and Krautblatter (2007)	Talus, rock fall, ground-penetrating radar, stratified scree
Morche et al. (2007)	Fluvial sediment budget, high-magnitude flood, landslide dam failure, geomorphic coupling
Götz and Schrott (2007)	Sediment budget, paraglacial concept, sediment cascade
Schneevoigt et al. (2008)	Landform detection, sediment storage, remote sensing, image segmentation
Morche et al. (2008)	Hydrogeomorphology, fluvial sediment transport, tethered balloon, stage discharge relation
Heckmann et al. (2008)	Talus cone/debris flow complex, debris flow, recurrence interval, Sediment budget
Morche et al. (in press)	Sediment transport, sediment cascade, sediment balance, terrestrial laser scanning
Krautblatter et al. (in press)	Rock fall, sediment budget, cliff retreat, magnitude-frequency

Study Area

REINTAL VALLEY

Previous investigations within the joint project "Sedimentary Cascades in Alpine Geosystems" have provided a detailed overview of the prominent geomorphic forms and dominant processes in the Reintal Valley, as well as details about the physiographic character (Table 1). Additionally, the Reintal valley is a key test site of the I.A.G. SEDIBUD Working Group and a selection of key data are stored in the database (http://www.geomorph.org/wg/wgsb.html).

The Reintal Valley is a formerly glaciated, U-shaped valley located in the Bavarian Alps approximately 80 km south of Munich (Fig. 1). The basin lithology is comprised of homogeneous limestone (Wettersteinkalk). The valley is fragmented into subsystems by large landslide deposits; upstream of the barriers areas were dominated by sedimentation (Phase 2 after Hewitt, 2006). The lowermost landslide dam at the lake Vordere Blaue Gumpe (VBG) failed in 2005. The interruption complex, the dam, was incised and partly removed by a high-magnitude flood event and by subsequent flow. Hence, the downstream channel reach is now in Phase 3 (after Hewitt, 2006). Preliminary results show an increasing bedload transport during the first post-dambreak field season (Morche et al., 2008a). The most affected channel reach of the Partnach River in the Reintal Valley between the former lake VBG and the outlet of the catchment is the focus of our current investigations.

THE LAKE HISTORY AND THE DAMBREAK FLOOD EVENT

The dam of the VBG was created by a landslide that must have occurred around A.D. 1800. Morche et al. (2006) dated the event relatively precisely by means of historical data (maps, sketches, paintings). During the 19th and 20th centuries the lake was subsequently filled with sediments. The growth of the delta was observed by interpretation of aerial photographs, and since 2000, by terrestrial geodetic surveying (Morche et al., 2006). Delta sedimentation was also observed by Sass et al. (2007), who carried out ground-penetrating radar surveys. The different delta stages can be clearly seen as foreset bed structures in the radargrams (Sass et al., 2007).

Following a wet period, a thunderstorm hit the Reintal Valley on 22/23 August 2005, and the resultant flood caused the dambreak. The peak outflow was estimated according the methods of Costa (1988), to be in a range between 26 and 50 $m^3\ s^{-1}$ (Morche et al., 2007), and more than 9500 m^3 of water were released in a short time. The dam was lowered about 3 m and in the first downstream reach, more than 100,000 t of sediment were eroded. The sediments were deposited in the proximal downstream channel reaches (300 to 700 m downstream of the former dam), indicating a very high peak discharge. The flood wave attenuated rapidly further downstream. A similar pattern was recently reported by Kershaw et al. (2005) for a moraine dammed-lake outburst flood in British Columbia. Plan form changes of the Partnach River channel of up to 10 m were recognized, and only 25% of the eroded sediment mass was exported from the catchment (Morche et al., 2007).

Methods

FLOOD STAGE MAPPING

Photographs were taken during the falling limb of the flood. The flood stage level was mapped during a field campaign in September 2005 using freshly deposited material on terraces, bed load impact structures on trees, and organic debris deposited in trees and on the banks. All flood marks could clearly be identified even the year after the flood, when the cross sections were surveyed and the particle counts were carried out. The area affected by the dambreak flood was determined by interpretation of official orthophotographs (©Landesamt für Geoinformation und Vermessung Bayern). The extent of the flood covered the whole valley floor of about 0.06 km^2, which is three times larger than the area inundated by a previous flood in 2003 (Fig. 2).

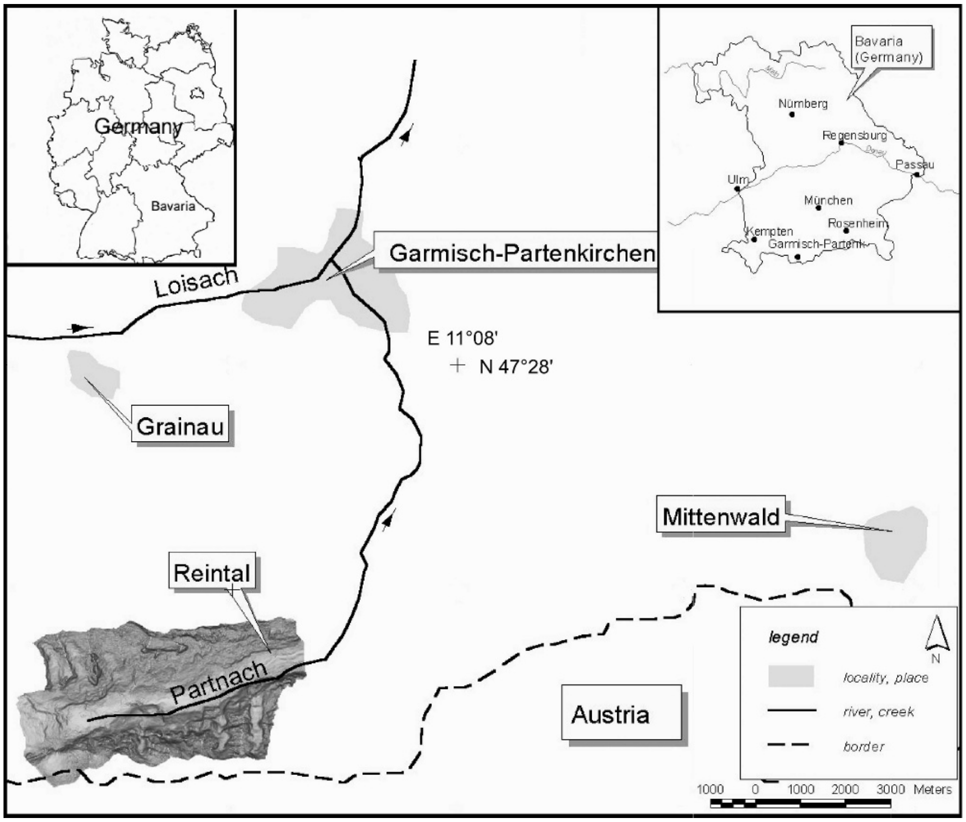

FIGURE 1. Location of the study area. Coordinates are Easting and Northing.

GEODETIC SURVEYS

Geodetic surveys using an ELTA Rec ZEISS tachymeter were carried out to determine the longitudinal profile and the gradient of the channel. The survey follows the study design of the previous observation periods (Morche et al., 2008b) with errors in vertical and horizontal dimensions below 1 cm. Several hundred points were measured on the channel bed along the line of maximum flow velocity. The longitudinal profile in 2003 had a mean point spacing of 2.3 m, 3.6 m in July and August 2005, and 6.3 m in September 2006 profiles. The data of the 2006 geodetic survey were then used for the calculation of the gradient (I in m m^{-1}).

CROSS SECTIONS

During the field campaign, 13 cross sections were surveyed. Every cross section covers the post-dambreak bankfull level. At each cross section, the bankfull discharge (Q in $m^3\ s^{-1}$) was calculated using the channel gradient (I), hydraulic radius (R in m), and the cross sectional area (A in m^2) in Manning's flow equation. Manning's n was determined with particle size data following pre-dambreak investigations. The methodological procedures including a discussion of the crucial roughness parameter are described in detail in Morche et al. (2008b). Further on, stream power (Ω in W m^{-1}), specific stream power (ω in W m^{-2}), and bed shear stress (τ_0 in N m^{-2}) were determined for each cross section.

The bench marks of the seven study sites measured in the previous observation periods were damaged during the dambreak flood. Where possible the bench marks were relocated at their previous position knowing the coordinates from former geodetic surveys. In the case of bank erosion or deposition, the cross section was expanded. An additional six new cross sections were installed in order to refine the spatial resolution. Coupling the data from the geodetic and cross section survey and the particle analysis (see below) we were able to document downstream trends in grain size and shape and stream power. Recently, the investigation of the downstream variation in e.g. stream power has gained growing importance in fluvial geomorphology. Knighton (1999) showed the downstream variation of total and specific stream power in rivers of the Trent River catchment (U.K.). Reinfels et al. (2004) investigated downstream trends of channel gradient as well as total and specific stream power in the Bellinger River catchment (Australia).

SURFACE PARTICLE CHARACTERISTICS

At every measured cross section (except cross section 3) a modified Wolman particle count (100 particles) was carried out in the field. The grain size composition of the bed sediment was determined by sieving the samples in half ϕ-units ($\phi = -\log_2$(D in mm)) electronically using an Excel spreadsheet. The size range of the intermediate axis of all 1200 measured particles is 3 to 1600 mm. It was possible to calculate the principle percentiles as well as the sediment sorting coefficient according to Folk and Ward (1957) knowing the particle size distribution. Finally, the ϕ-values (except the sorting coefficient) were recalculated in metric units.

In addition to the intermediate axis of each particle, the shortest and longest axes were measured to compute the shape of each particle. Particle shape characteristics were determined by applying the widely used triangular shape diagram of Sneed and Folk (1958). We used a modified version of the Tri-Plot software developed by Graham and Midgeley (2000) to calculate the particle shape classes.

Results

LONGITUDINAL PROFILE

The changes of the longitudinal profile of the Partnach River are shown in Figure 3. The river profile was surveyed in 2003,

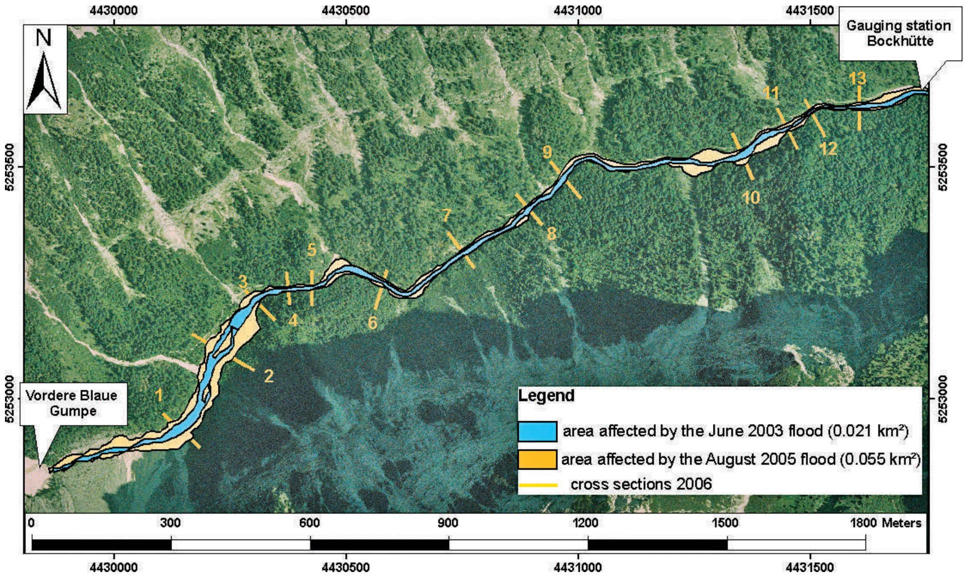

FIGURE 2. Map of the Partnach River channel reach (investigated from the Vordere Blaue Gumpe dam to gauging station Bockhütte); background: orthophotograph from 18 July 2006 (©Landesamt für Vermessung und Geoinformation, permission for use and publication from 6 February 2007, reference number: VM3831B-oN/7-0138.). The situation round the Vordere Blaue Gumpe is shown in detail on a photograph in Fig. 7.

July/August 2005, and September 2006. After a first flood event in July 2005 detailed geodetic surveys of the channel bottom could only be carried out to a 1050 m downstream distance. Since the survey could not be finished due to the occurrence of the dambreak event, the 2005 profile is shorter. However, the July 2005 event eroded the channel bed significantly (Fig. 3). During the dambreak flood event a large amount of sediment (>10^5 t) was eroded in the upstream reach (0–300 m) and most of it deposited directly in the downstream reaches (Morche et al., 2007). The channel bed of the Partnach River was aggraded several meters compared to the short July 2005 profile and the entire post-dambreak channel bed is elevated compared to the 2003 profile. The aggradation is about 9 m at the beginning of the profile immediately downstream of the steepest channel reach and decreases in the further river course (Fig. 3). Major plan form changes of the Partnach River channel occurred during the dambreak event when large parts of both banks were disturbed (Morche et al., 2007). During the first post-dambreak field season no significant changes in the plan form were recognized. The lateral input of the main sediment sources in the same year was surveyed by Morche et al. (2008a) and Heckmann et al. (2008) using terrestrial laser scanning and electronic tachymeters.

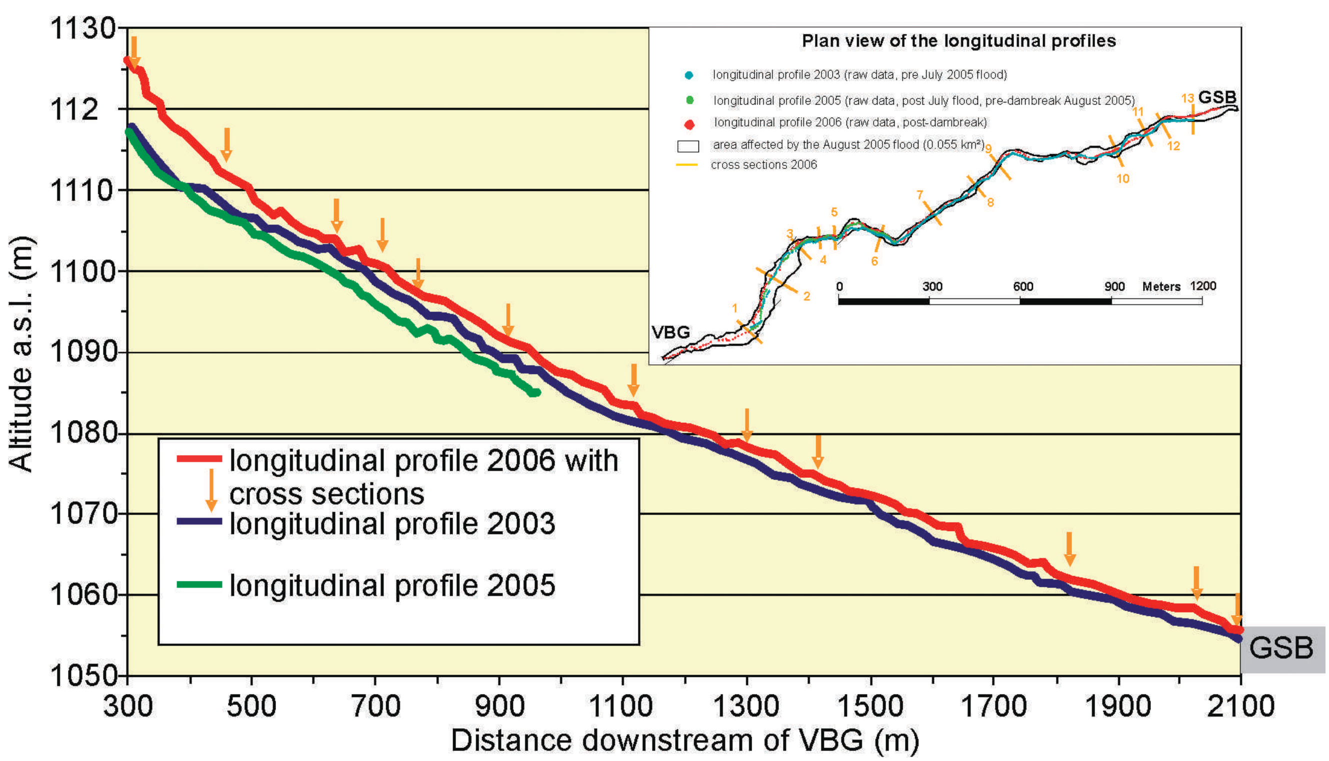

FIGURE 3. Longitudinal profile of the Partnach River (2003, 2005 and 2006), VBG = Vordere Blaue Gumpe, GSB = gauging station Bockhütte.

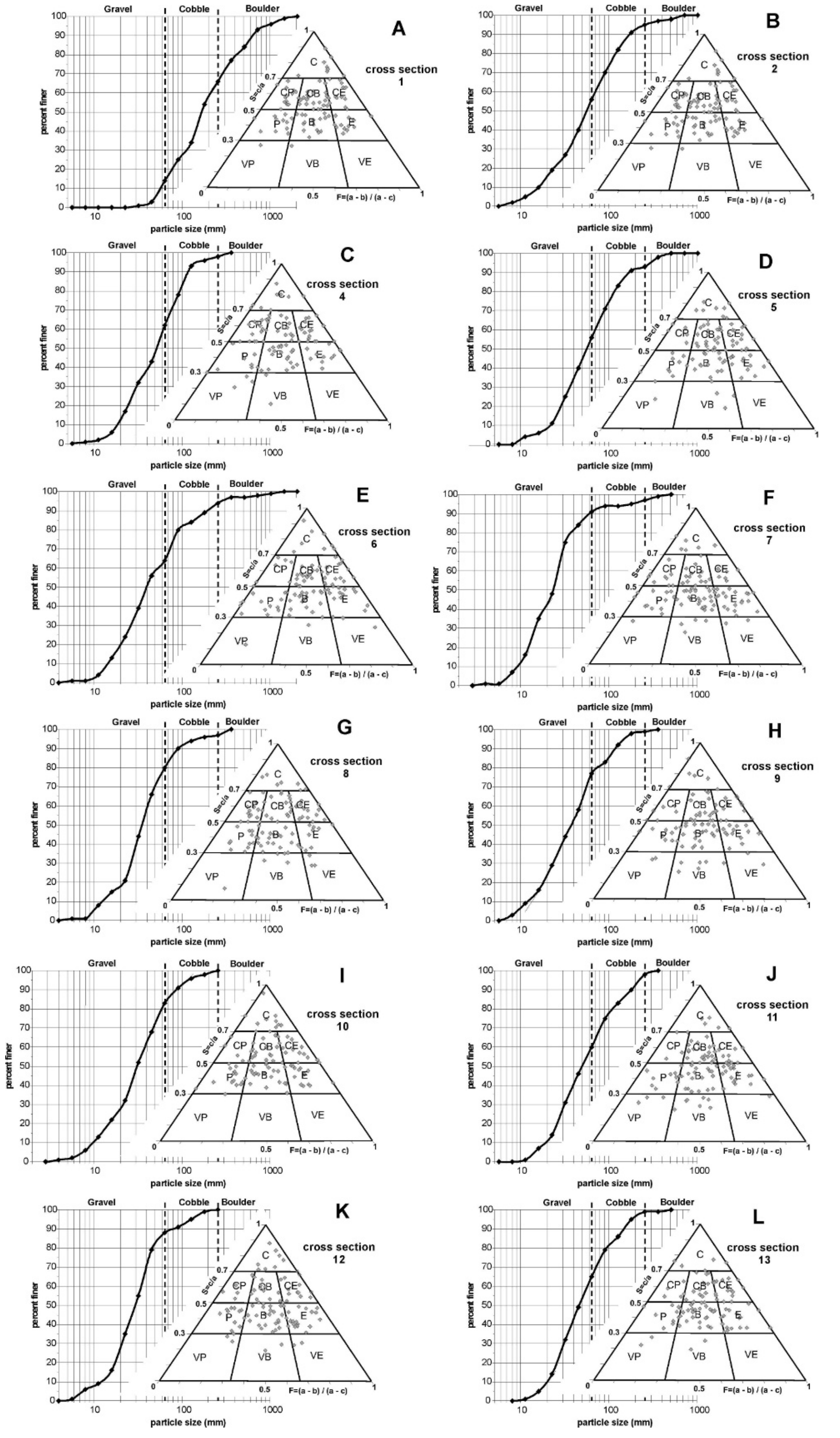

FIGURE 4. Particle size and shape (Sneed and Folk triangular diagram) distributions at the different cross sections, C—compact, P—platy, B—bladed, and V—very.

DOWNSTREAM VARIATION OF PARTICLE CHARACTERISTICS

The particle size and shape distributions of the bed material sampled in 2006 are shown in Figure 4 and Table 2. The bed material of cross section 1 is very coarse with about 35% boulder size particles, 50% cobbles, and about 15% gravel (CS 1; Fig. 4A), and the upstream gradient is the highest (0.13). Here, the largest particle (1.6 m) moved by the dambreak flood was found (Table 2). Also, the D_{16} (56 mm), D_{50} (169 mm), and D_{84} (512 mm) sizes were the coarsest of all of the cross sections (Table 2). In general, the particle sizes decrease further down-

TABLE 2

Particle size and shape characteristics and hydraulic parameters of the surveyed cross sections at bankfull level. L—distance downstream the dam, $D_{16,\ 50\ ,84}$—particle size where 16, 50 or 84% are finer, D_{max}—largest particle, C—compact, P—platy, B—bladed, E—elongated, VP—very platy, VB—very bladed, VE—very elongated, Ω—stream power, ω—specific stream power, τ_0—bed shear stress, I—gradient (m m^{-1}), Q—discharge, V—mean velocity, A—cross sectional area, W—width, R—hydraulic radius, n.d.—not determined. Note: no particles were measured at cross section 3. Therefore, particle size data of cross sections 2 and 4 were averaged and used for the calculation of the bankfull discharge at cross section 3.

Cross section	Distance VBG (m)	D_{16} (mm)	D_{50} (mm)	D_{84} (mm)	D_{max} (mm)	$S_{(F\&W)}$	C (%)	CP (%)	P (%)	VP (%)	CB (%)	B (%)	VB (%)	CE (%)	E (%)	VE (%)	Ω (W m^{-1})	Ω (W m^{-2})	τ_0 (N m^{-2})	I	Q (m^3 s^{-1})	V (m s^{-1})	A (m^2)	W (m)	R (m)
1	320	56.4	168.9	512	1600	1.37	8	12	12	1	22	20	1	11	13	0	878219	17923	989	0.13	684	8.5	80.3	49	0.77
2	519	20.1	56.2	138	570	1.38	6	9	11	2	13	26	4	10	17	2	787583	29720	1636	0.09	886	15.7	56.5	26.5	1.84
3	652	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	31157	1731	273	0.04	79	5.8	13.6	18	0.69
4	735	21.9	51.5	104	360	1.09	8	9	10	4	16	24	2	12	15	0	61248	2889	375	0.05	124	6.9	17.9	21.2	0.76
5	806	25.6	56.2	134	500	1.27	8	6	8	2	20	23	4	14	15	0	70835	4427	478	0.04	179	7.9	22.6	16	1.21
6	1001	17.6	40.1	128	1360	1.41	8	5	14	1	16	21	2	16	14	3	47870	2046	296	0.03	162	5.9	27.3	23.4	1
7	1214	11.3	23.2	45.3	440	1.28	6	7	14	1	13	29	4	6	18	2	12917	844	163	0.03	44	4.8	9.1	15.3	0.55
8	1394	16.9	35.2	73.5	350	1.13	7	11	14	1	13	22	5	15	9	3	27530	2573	312	0.04	70	6.6	10.5	10.7	0.79
9	1494	16	37.1	94.1	260	1.33	5	4	10	2	14	28	6	12	17	2	2395	172	58	0.01	24	2.6	9.3	13.9	0.59
10	1935	12.2	30.9	66.8	220	1.21	9	4	14	1	21	25	0	11	15	0	15041	970	178	0.03	51	4.8	10.5	15.5	0.6
11	2030	23.5	50	135	330	1.23	5	4	7	3	20	25	7	7	20	1	24768	1848	281	0.03	84	5.8	14.4	13.4	0.95
12	2079	16	29.3	54.9	190	0.95	8	5	10	3	12	28	2	13	17	2	23564	2223	287	0.03	80	6.7	11.8	10.6	0.97
13	2217	23.5	46.3	116	380	1.11	4	4	8	2	16	34	2	13	17	0	9566	825	166	0.03	32	4.2	7.7	11.6	0.56

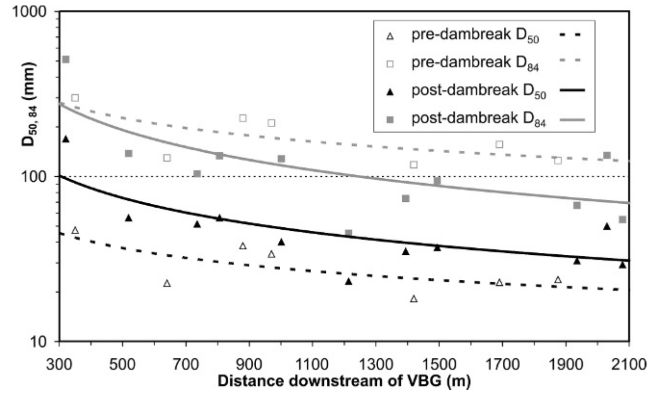

FIGURE 5. Pre-and post- dambreak downstream trends of particle size (pre-dambreak data is taken from Morche et al., 2008b).

stream with an increasing amount of gravel and cobble particles (Figs. 4B–4L). Downstream of cross section 6 only a few or single boulders were found in the cross sections on the Partnach River bed.

Compact-bladed and bladed particles dominated the shape distribution (Fig. 4A, Table 2). On the further river course downstream the dominant particle shape is "bladed" immediately followed by "compact bladed" (Figs. 4B–4L, Table 2). This shape class was determined to be also dominant for the large talus cone/debris flow complex (Morche and Schmidt, 2005), which is recognized to be the most important sediment source during the dambreak event (Morche et al., 2007) and in 2006, too (Heckmann et al., 2008; Morche et al., 2008a).

Pre- and post-dambreak particle size characteristics show a similar downstream variation. For both conditions, a general downstream fining trend exists (Fig. 5, Table 3). However, while the post-dambreak D_{50} is coarser than the pre-dambreak one, the D_{84} is finer (Fig. 5).

The channel bed sediment consists of a smaller number of particle size classes. Due to the large flood deposits in and nearby the channel, abundant sediment supply can serve as an explanation, bearing in mind that the source of the flood-deposited sediments was one single large talus cone/debris flow complex right below the Vordere Blaue Gumpe (Heckmann et al., 2008; Morche et al., 2007).

DOWNSTREAM VARIATION OF STREAM POWER AND BED SHEAR STRESS

Total and specific stream power as well as bed shear stress show clearly visible downstream decreases in the first post-dambreak observation period compared to the gradual declines and power law exponents (<1) of the pre-dambreak trends (Fig. 6, Table 3). Total stream power measured at the beginning of a particular channel reach is one to two orders of magnitude greater after dambreak. Further downstream, a reduced difference between post- and pre-dambreak stream power is evident. In general the post-dambreak values reached at the beginning of the study reach are unusually high. The total stream power of the Partnach River is 8.8×10^5 W m^{-1} 320 m below the former VBG dam and shows the large energy expenditure that could be reached if the bankfull level were reached. But, in fact, the bankfull level is a crucial parameter in this section where most of the eroded material from the first channel reach is deposited. The bankfull level is defined as the lowest value of the width-depth ratio (Knighton, 1998, p. 163). Using this criterion for determining the

TABLE 3

Power law regression equations ($Y = aX^b$) between downstream distance (X) and pre- and post-dambreak D_{50}, D_{84}, Ω, ω, and τ_0 (all Y) and the levels of determination (R^2).

	Pre-dambreak			Post-dambreak		
	a	b	R^2	a	b	R^2
D_{50}	748	−0.54	0.82	$3.3*10^3$	−0.61	0.55
D_{84}	464	−0.41	0.50	$1.6*10^4$	−0.71	0.49
Ω	$3.9*10^3$	0.03	0.06	$1.6*10^{12}$	−2.18	0.65
ω	$8.2*10^3$	−0.39	0.22	$1.2*10^9$	−1.56	0.51
τ_0	$4.9*10^3$	−0.49	0.38	$2.7*10^6$	−0.97	0.50

cross sectional area at the first cross section a value of 80 m^2 was determined and used in the continuity equation for calculation of bankfull discharge.

The dambreak outflow must have been like a burst, and the downstream traveling flood wave attenuated more and more with increasing distance. The highly unstable conditions of the event are still imprinted on the river morphology. For example, the bankfull level after the dambreak event is mainly determined by flood deposits which created new and in some cases much higher banks. Bankfull discharge, mean velocity, and cross sectional area generally decrease in the downstream direction (Table 2), and the general laws of downstream hydraulic geometry (Leopold and Maddock, 1953) are not fulfilled. So the steep falling of the empirically derived bankfull discharge from cross section 1 to cross section 3 cannot be explained only by transmission losses but also by the large amounts of coarse sediments deposited in that reach on the banks and on the channel bed (Morche et al., 2007).

The new banks consist of loose deposited gravel- to boulder-sized sediments, and are unstable and therefore vulnerable to fluvial erosion. Therefore, it can be expected that during the next flood(s) morphological adjustments will lower the bankfull level (to the pre-dambreak state?) and consequently the total and specific stream as well as bed shear stress power especially in the channel to near the first cross sections.

Discussion and Conclusions

Variation of downstream trends of bed particle characteristics (size and/or shape) can be explained by different underlying bedrock lithologies (Knighton, 1982; Werritty, 1992), sediment supply by tributaries (Rice, 1999), and the fluvial processes of selective sorting and abrasion (Powell, 1998; Surian, 2002). In the special case of a dambreak event in the Rubicon River, California, Scott (1967) and Scott and Gravlee (1968) observed a similar downstream fining of the flood deposited sediments. It is explained with conditions of continuously decreasing competency during the flood and progressive sorting (Scott and Gravlee, 1968). Due to the homogeneous lithology of the Reintal Valley, lateral sediment supply and selective sorting were the main controls of the bed material particle characteristics of the Partnach River in pre-dambreak times (Morche and Witzsche, 2006; Morche et al., 2008b). Previous investigations have shown an increase in boulder size immediately downstream of tributary slope channels (Morche and Schmidt, 2005). Debris flows and avalanches mobilize sediment on the slopes and supply the main channel—the way a typical sediment cascade works (Becht et al., 2005). Then the coarsest particles stay in the channel bed while the Partnach River is able to remove the finer ones. After the dambreak flood large amounts of sediment are available to fluvial transport processes. High sediment input from the main sediment sources (e.g. truncated talus cone and Vordere Blaue Gumpe Basin in Fig. 7) lead to transport conditions of equal mobility even during lower flows. All particle sizes are in motion when sediment is supplied to the channel—a finding that was evaluated, not quantified, during field visits in summer 2007, when a kinematic wave–like sediment slug moving down the disturbed channel reach (Fig. 7) was recognized by the first author (see two supplemental videos of the sediment slug), and by bed load measurements (Morche et al., 2008a).

During the first post-dambreak observation period, large amounts of sediment were supplied by different sediment stores along the river course. Once supplied to the Partnach River the sediment was transported during different bed load periods. In total, more sediment was exported from the observed channel reach than supplied from lateral and upstream sources (Morche et al., 2008a). Hence, the sediment balance was negative. The net total annual sediment export from the catchment was 2900 t and about two magnitudes higher than in pre-dambreak times (Morche et al., 2008a). This net export indicates channel bed degradation since the dambreak event in August 2005. But, even in September 2006, one year after the main flood period, the channel bed was higher than before the dambreak (Fig. 3). Consequently, the channel bed immediately after the dambreak flood must have been even much higher.

Although channel bed degradation and sediment export obviously dominated after the dambreak event (annual time scale), the Partnach River system can be placed in Hewitt's phase 3 with trenching of the barrier and downstream sedimentation. The start of phase 4 will be reached when the Partnach River channel bed is below the longitudinal profile of the pre-dambreak conditions (see Fig. 3).

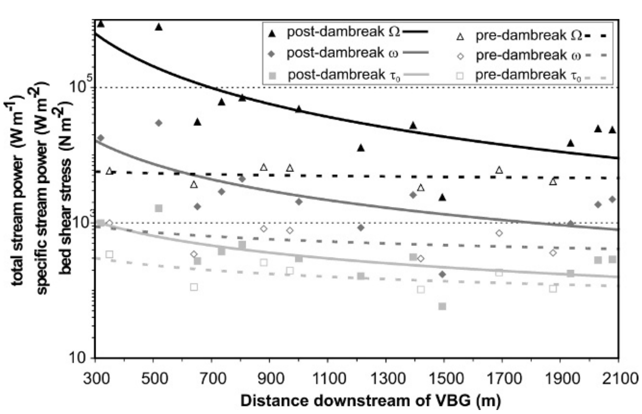

FIGURE 6. Pre-and post- dambreak downstream trends of stream power and bed shear stress (pre-dambreak data is taken from Morche et al., 2008b).

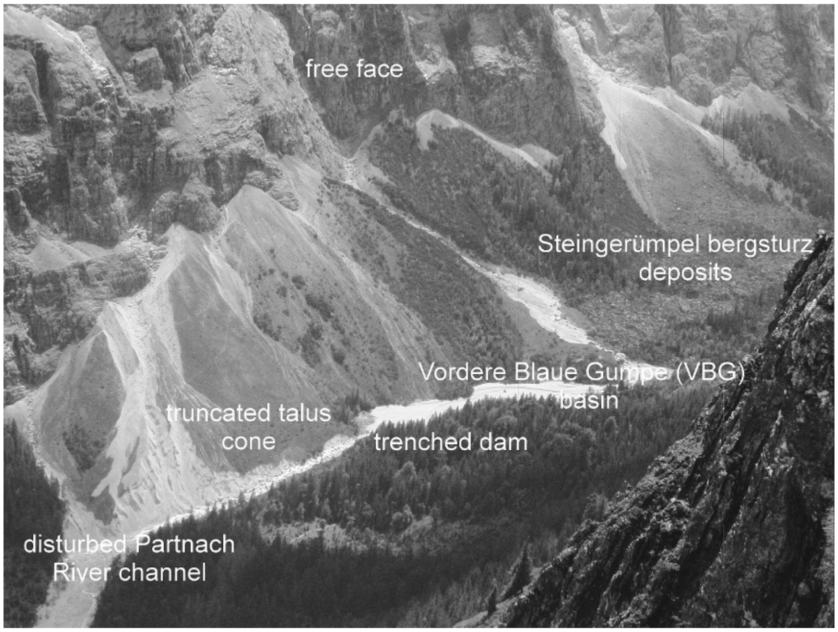

FIGURE 7. Photograph of the post-dambreak situation of the most affected reach, view southwest (background photo: David Morche 11 July 2007).

The first two cross sections are located in the most affected area (Figs. 2 and 7) and have very high values of bankfull discharge, stream power, and bed shear stress. The most important factor in their calculation is the bankfull cross sectional area, which was determined strictly according to the Knighton (1998) criterion of the lowest width-depth ratio. Within the most affected channel reaches, which are represented by the first two cross sections, about 63,000 t were deposited during the dambreak flood (Morche et al., 2007). We expect that the channel will adjust to a lower bankfull level in the near future, when the proximal flood deposits, now determining the bankfull level, will be exhausted.

Applying Hewitt's phase model (see above) to the Vordere Blaue Gumpe dam in the Reintal Valley, the following timetable of the different phases can be provided:

- Phase 1: around 1800 (landslide),
- Phase 2: around 1800 to 2005 (dambreak event),
- Phase 3: since the dambreak event 2005 (after incision of the dam),
- Phase 4: soon, after the next flood(s),
- Phase 5: centuries or even millennia, when sediment stores (0.07 km^3 after Schrott et al., 2003) are mainly removed and bed rock contacts surface.

Wherever dambreak events occur, massive destruction and landscape disturbance follow. The degree to which the channel will adjust to the new equilibrium will depend on future discharges, riparian vegetation growth, comminution rates of sediment clasts, sediment transport capacity, and bed armoring processes. Studies of geomorphic impacts of outburst floods in British Columbia have shown that the recovery of a river system to a near pre-event state may take decades (Nostetuko River; Clague and Evans, 2000) or even centuries (Noeick River; Desloges and Church, 1992). In order to observe the ongoing response of the Partnach River system to the failure of the Vordere Blaue Gumpe dam in August 2005 in terms of channel and bank adjustment as well as sediment transport dynamics, first approaches (terrestrial laser scanning, bed load measurements, hydrogeomorphological field work) presented by Morche et al. (2008a) and in this study will be widened and intensified in an ongoing research project.

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