

The continuous measurement of bedload discharge in a large alpine gravel bed river

Mesure en continu du charriage de fond dans une rivière alpine à lit graveleux avec une trappe à fente

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ABSTRACT

The objective of this paper is to analyze the efficiency of a bedload-measuring trap for continuous sediment measurements. The trap is implemented into the river-bed of the Drau, located in Southern Austria. At the trap site the mean annual discharge is $64 \text{ m}^3 \text{ s}^{-1}$, the slope is about 0.002 and the mean subsurface grain diameter is about 28 mm. Two criteria, hydraulic efficiency and sampling efficiency, are used to evaluate the performance of the trap. The hydraulic efficiency as well as the sampling efficiency are shown to be high. The advantage of the trap is that continuous and automatic bedload transport measurements can be obtained even in wide, alpine gravel bed rivers. We demonstrate that continuous bedload data are useful with respect to identifying initiation of motion. The comparison with formulas shows significant deviations between measurements and calculations. In such a supply limited river-bed, where bedload often moves over an armour layer, it is apparent that local hydraulic conditions explain only a fraction, about one third of the variation in the weak bedload flux.

RÉSUMÉ

L'objectif de cet article est d'analyser l'efficacité d'une trappe à sédiments pour la mesure en continu du charriage. La trappe a été installée dans le lit de la rivière Drau, située dans le sud de l'Autriche. À l'endroit où est située la trappe le débit moyen annuel est de $64 \text{ m}^3 \text{ s}^{-1}$, la pente est environ 0,002 et le diamètre moyen des graviers constituant le lit est voisin de 28 mm. Deux critères, l'efficacité hydraulique et l'efficacité de l'échantillonnage, ont été retenus pour évaluer les performances de la trappe. Suivant ces deux critères, l'efficacité de la trappe s'est avérée bonne. L'avantage principal de la trappe étudiée est qu'elle permet de réaliser des mesures continues et automatiques du charriage de fond même dans des rivières larges à lit de gravier. Nous démontrons que les données de charriage continues sont très utiles en ce qui concerne l'analyse du déclenchement du mouvement des sédiments. La comparaison avec des formules montre qu'il existe des écarts significatifs entre les mesures et les calculs. Il apparaît que, dans une telle situation, où le transport est limité par l'approvisionnement et où le charriage de fond se déplace au-dessus d'une couche protégée, les conditions hydrauliques locales n'expliquent qu'une fraction, environ un tiers, de la variation du flux de charriage.

Introduction

Most Alpine rivers have been regulated over the past one hundred years to control the bedload regime by implementing sedimentation reservoirs and bedload retention measures. These have caused dramatic technical and ecological consequences (Habersack and Nachtnebel, 1997). To reduce adverse effects of river-bed degradation, such as lowering of groundwater level in riverine zones and to initiate dynamic gravel bars in rivers, adequate measures have had to be planned. During the discussion of alternate engineering measures, it became evident that a lack of data concerning bedload flux and grain size distribution limited the calibration of numerical sediment transport models. A sensitivity analysis has demonstrated that the assumed and partially measured natural variability of input data causes significantly different modeling results and may lead to wrong decisions (Habersack, 1998).

Long-term datasets for the Drau River (Carinthia, Austria) show a spatially variable bed instability, with reaches undergoing aggradation and others degradation, the latter to a maximum of

1.5 m in 60 years (Habersack and Nachtnebel, 1998). Due to lack of sediment discharge data, bedload discharge measurements with a Large Helley-Smith sampler were initiated in 1994 (Habersack, 1997a, b). This sampler allows measurements of bedload discharge to be made with a high spatial resolution, the temporal limitation leading to an inability to record bedload pulsation. Therefore, it was decided to develop a sampler for the continuous measurement of bedload discharge. The aim of this paper is to analyze the possibility of utilizing a slot sampler for the measurement of bedload discharge in large, gravel bed rivers. Leopold and Emmett (1976) developed the conveyor belt slot system at East Fork River, Wyoming. The Vortex tube system was deployed in Oak Creek, Oregon (Milhous, 1973), in the Torlesse Stream, New Zealand (Hayward and Sutherland, 1974) and in Virginio Creek, Italy (Taconni and Billi, 1987). The weighing slot sampler system (Reid et al., 1980) has been used in Goodwin Creek, Mississippi (Kuhnle et al., 1988), Nahal Yatir (Laronne et al., 1992) and Nahal Eshtemoa, Israel (Powell et al., 1995), as well as in the Mediterranean Rio La Tordera, Spain (Garcia et al., 2000); recently it has been deployed in Nahal Rahaf and Nahal

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Kana'im, two channels in the extreme arid environment of the Dead Sea, Israel (Laronne and Cohen, 1998). These installations have been based on the assumption that the trap efficiency of slot samplers is very high.

Measurement device and study site

In order to quantify bedload transport rates and to characterize bedload texture, a measurement technique was developed for the river Drau. The sampler is essentially a Birkbeck-type automatic monitoring slot sampler (Reid et al., 1980).

The Drau has a bed width of 40 m, a longitudinal bed slope of 0.18 percent, and subsurface mean grain diameter of 28 mm at the monitoring site (Fig. 1). The mean annual discharge is $64 \text{ m}^3 \text{ s}^{-1}$. It is glacier-meltwater fed during spring and summer. The bedload monitoring system differs from previous samplers, in that this is the first to be installed in a large perennial river, where minimal flow depth and velocity are 0.6 m and 1 m s^{-1} , respectively. This necessitates (1) a large volume for the trap and (2) that the entire data logging unit be submersible.

Development of the slot sampler

With boundary conditions given by flow velocity, river width, maximum trap dimensions and maximum size of transported material, the magnitude of the step length and height are needed for the computation of the slot length and slot opening. Step lengths and step heights are dependent on the Shields-parameter Fr^* as a basic value for the forces acting on the grains and the relative grain density (DVWK, 1992). Using these relations and the following equations, the results of Fig. 1 were derived.

$$Fr^* = \frac{\mu v^*{}^2 \eta}{\rho' g d} \quad (1)$$

$$\eta = \left(\frac{0.4}{\sqrt{d/d_a}} + 0.6 \right)^{-2} \quad (2)$$

$$\frac{d_a}{d_{50}} = 1.6 \tilde{\sigma}_g^{-0.28} \quad (3)$$

$$\tilde{\sigma}_g = \frac{d_{84}}{d_{16}} \quad (4)$$

with Fr^* as Shields parameter by Shiquiang and Ren (1987), v^* as friction velocity, μ as ripple-factor (Bauer, 1965), η as hiding factor (Day, 1980), ρ' as relative density, g as acceleration due to gravity, d as grain size and d_a as grain size for $\eta = 1$.

Based on the results of the theoretical considerations and practical boundary conditions, the following two part system was designed, consisting of

- A fixed concrete tube of 2 m diameter and 1.5 m depth. This part was installed in the river bed so that the upper part of the concrete is flush with the bed.

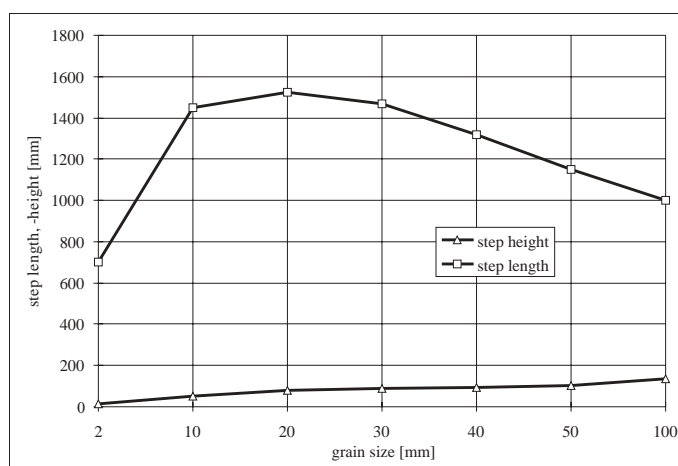


Fig. 1. Step lengths and heights for individual grains at the River Drau.

- Two steel boxes, one located inside the other. These can be withdrawn and reinserted into the concrete tube. The steel tube has a variable slot opening (Fig. 2). A pressure pillow, pressure transmitter and data logger are located between the two steel boxes. Slot width and slot length were 150 mm and 1585 mm, respectively.

Implementation of the slot sampler

The slot sampler was implemented in the River Drau near Dellach during the low water period of the year 1992 (Fig. 2).

Hydraulic and sampling efficiency of the slot sampler

The hydraulic and the sampling efficiency were investigated in order to determine the performance of the slot sampler under Drau River conditions.

Hydraulic efficiency

Knowledge of the hydraulic efficiency (α_H) is required for the evaluation of sampling device effectiveness. The hydraulic efficiency α_H is defined as:

$$\alpha_H = 1 - \frac{v_i}{v_o} \quad (5)$$

where v_i is average flow velocity inside the trap (on top of the trapped material) and v_o is average bottom flow velocity outside the trap (on the river bed).

Slot samplers should have very low velocities above and in proximity to trapped sediment, leading to maximization of α_H . We deployed an ACM-300D (Alec Electronic Co.; see Habersack et al., 1998), a 3-axis electromagnetic current meter capable of measuring flow velocity in three dimensions. It is designed to measure flow velocity based on Faraday's electromagnetic induction law. It has a sensitivity to measure flow velocity in the range of $0 - 3.0 \text{ m s}^{-1}$ with an accuracy of $\pm 2 \%$ or 0.005 m s^{-1} . Measurements were performed at a steady discharge of about $60 \text{ m}^3 \text{ s}^{-1}$, a

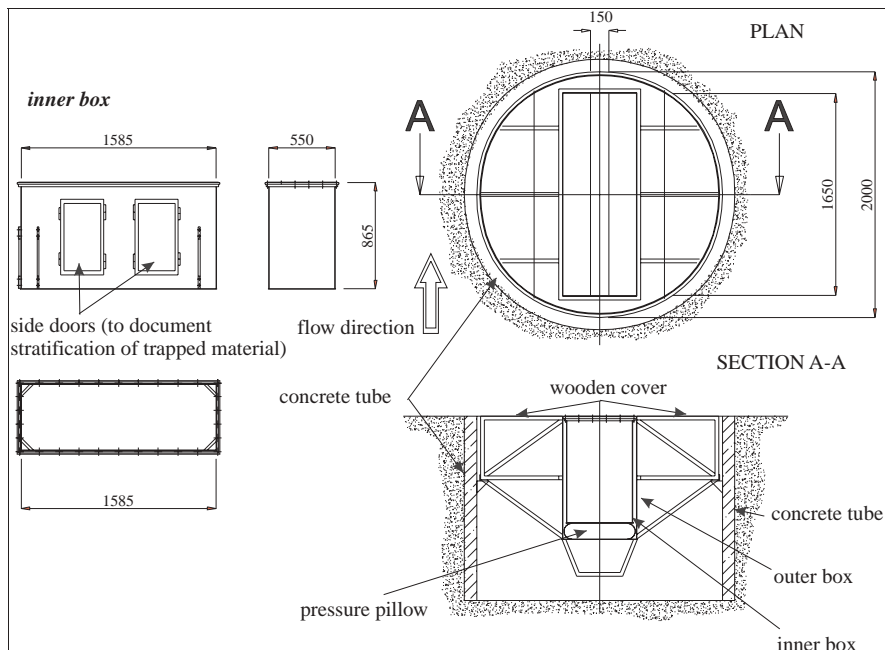


Fig. 2. Slot sampler at the River Drau.

flow depth approximating 1 m and flow velocity as high as 2.6 m s^{-1} .

Individual measurements lasted 1 minute at a frequency of 2 Hz. The measurements were undertaken from a small boat tied to the banks, such that boat location was accurately determined. Using the ACM-300 current meter, measurements were undertaken both in and around the slot. Those within the slot were performed at six stages of trap filling: 0, 20, 40, 60, 80 and 100 percent. The trap was filled with sediment using a long conical funnel. Four current metering verticals were chosen: about 1 m upstream of the trap, at the upstream end of the slot, at the centre of the slot and at the downstream end of the slot. At a vertical, velocities were measured 10 cm below the water surface, at mid-stream depth and at the level of the wooden trap cover. Additionally, they were measured at 5 cm below the top of the slot, in the middle of the

remaining water body within the slot and about 3 cm above the deposited sediment. Fig. 3 is the result of efficiency calculations based on flow velocity measurements and equation 5. It can be seen that the efficiency is greater than 90 percent up to and including 60 percent fill. At 80 percent fill the efficiency is 66 percent. The difference between efficiencies calculated for the upstream, central and downstream part of the box increases with filling stage. This derives from an essentially standing body of water at 60 percent fill, and due to significantly higher velocities occurring inside the trap at 80 percent fill (Habersack et al., 1998). At least four secondary flow cells with an upwelling tendency in the centre can be identified in the empty slot (Fig. 4). Due to the high efficiency and small absolute flow velocities ($< 0.1 \text{ m s}^{-1}$), this flow structure has a negligible effect on sediment mobilization within the slot.

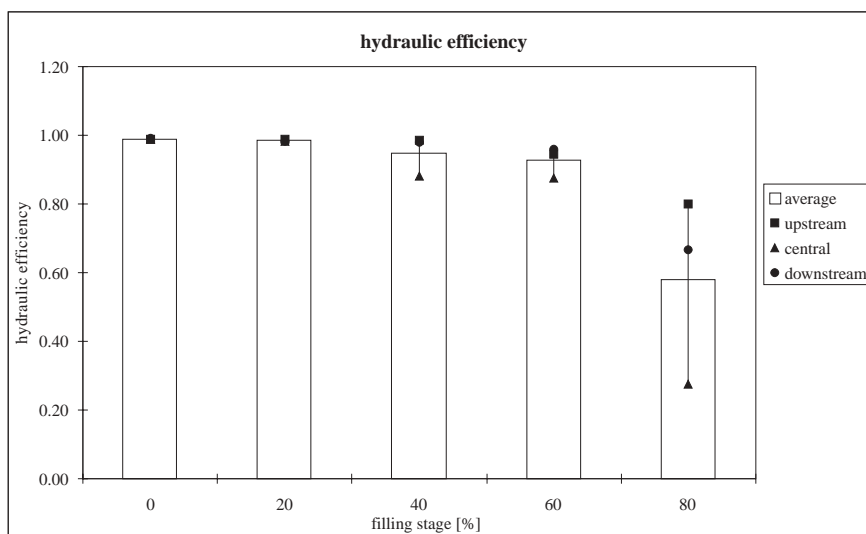


Fig. 3. Varying hydraulic efficiency with filling stage; average values, upstream, central and downstream efficiencies.

Sampling efficiency

The sampling efficiency α_S is defined as

$$\alpha_S = \frac{m_t}{m_n} \quad (6)$$

where m_t is trapped bedload discharge and m_n is bedload discharge occurring in Nature.

In order to evaluate the sampling efficiency of this slot sampler, the transport rates calculated from trap data were compared to those obtained by measurements using a Large Helley-Smith sampler. Low transport rates being observed during initiation of motion were used to compare naturally occurring bedload transport with measured values from the period of 17.3.1995 - 8.5.1995. The measurements with the Helley-Smith sampler showed that the lowest discharge when bedload transport was observed is about $57 \text{ m}^3 \text{ s}^{-1}$ (Habersack, 1997a). For the slot sampler initiation of motion started at $47 \text{ m}^3 \text{ s}^{-1}$. In order to evaluate the reason for this discrepancy, the grain size distribution of the slot sample was analyzed. Fig. 5 shows the result of 27 subsamples. Generally, the mean size of the material increases from the bottom ($d_{mIII} = 5-7 \text{ mm}$) to the top ($d_{mI} = 20-25 \text{ mm}$).

Furthermore, over the width of the box a grain size gradient occurs with larger sizes in the centre. This is particularly evident at the top of the sampler (samples AI, BI, CI). At the bottom of the sampler we encounter fine grained material (coarse sand), indicating that fine bedload was trapped at initiation of motion. Taking this into consideration, we conclude that the sampling efficiency of the trap is very high, slightly below or above unity; it is caused by the high hydraulic efficiency. This can be shown also by the comparison with Helley-Smith data, measured simultaneously near the trap location. In order to compare the results a truncation

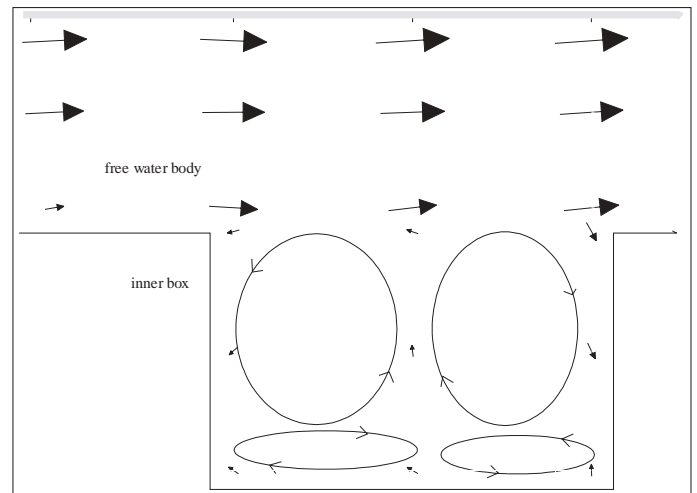


Fig. 4. Secondary flow cells inside the empty trap

at the mesh size of the Helley-Smith (0.25 mm) was performed. The result of the Helley-Smith measurement was $0.023 \text{ kg m}^{-1} \text{ s}^{-1}$ and was taken as bedload transport occurring in Nature. After truncation the related trap result was $0.029 \text{ kg m}^{-1} \text{ s}^{-1}$. This means that the sampling efficiency of the sampler is 79 percent of that of the trap.

The comparison between a slot sampler and a moveable, pressure difference sampler such as the Helley Smith should, however, be undertaken at an identical time and location. This was not the case in our comparison, from which we carefully conclude that the slot sampler is not necessarily more efficient than the Helley Smith. One reason for this is that the trap has a higher sampling efficiency, especially for weak bedload discharge. In order to define accurate efficiencies, additional laboratory investigations are required.

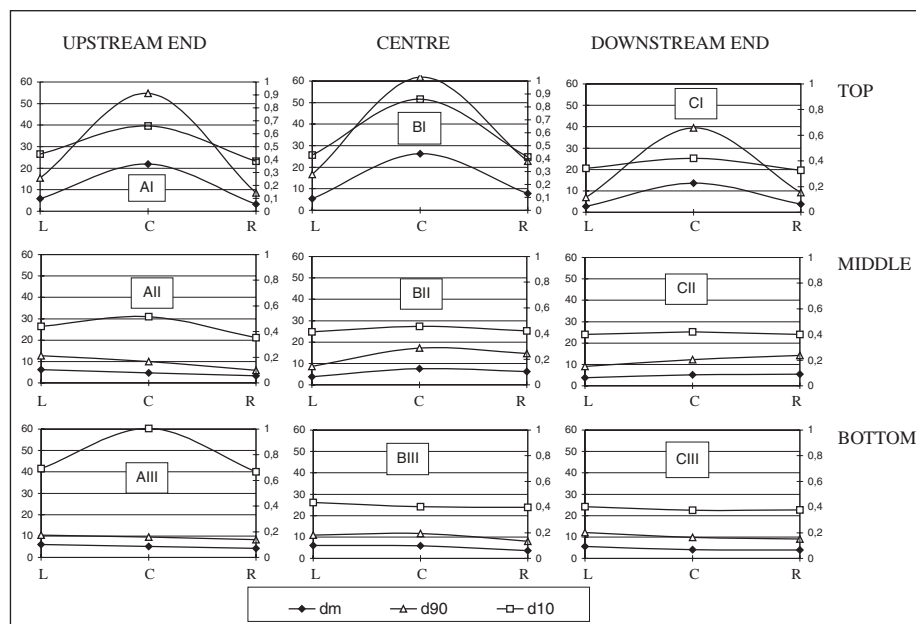


Fig. 5. Distribution of grain size within the trap from bottom (III) to top (I); A, B, C are subsample positions in flow direction at the various heights; x-axis: horizontal subsample position across the trap, (L=left side, C=center, R=right side), left y-axis: dm and d90 [mm]; right y-axis: d10 [mm].

Bedload transport

The River Drau is a glacier fed system with discharge increasing considerably during the snow melt period in April. The first automatic recording of bedload discharge took place in the year 1995. Fig. 6 shows the filling of the trap from April 25 until May 2. During this period of 7 days, altogether 1360 kg of bedload were sampled until the trap was full.

Initiation of motion

The slot sampler allows determining hydraulic conditions during initiation of motion, which took place at 14:00 on April 25, 1995 (Fig. 6).

Fig. 6. shows that the initiation of motion occurred during stage rise, which is dominated by surge effects caused by a water power plant located approximately 40 km upstream of the study site. For

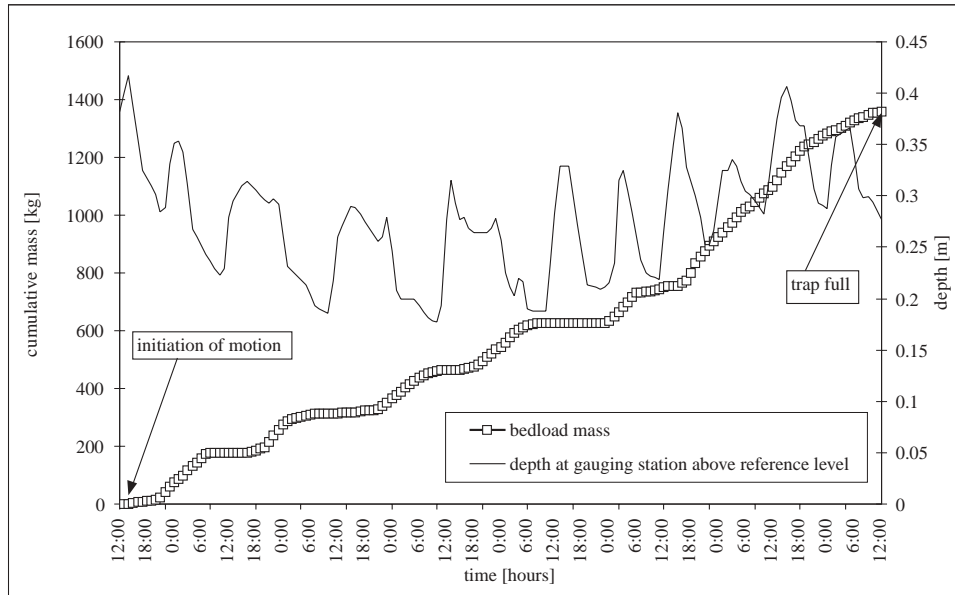


Fig. 6. Cumulative mass of bedload and water level changes.

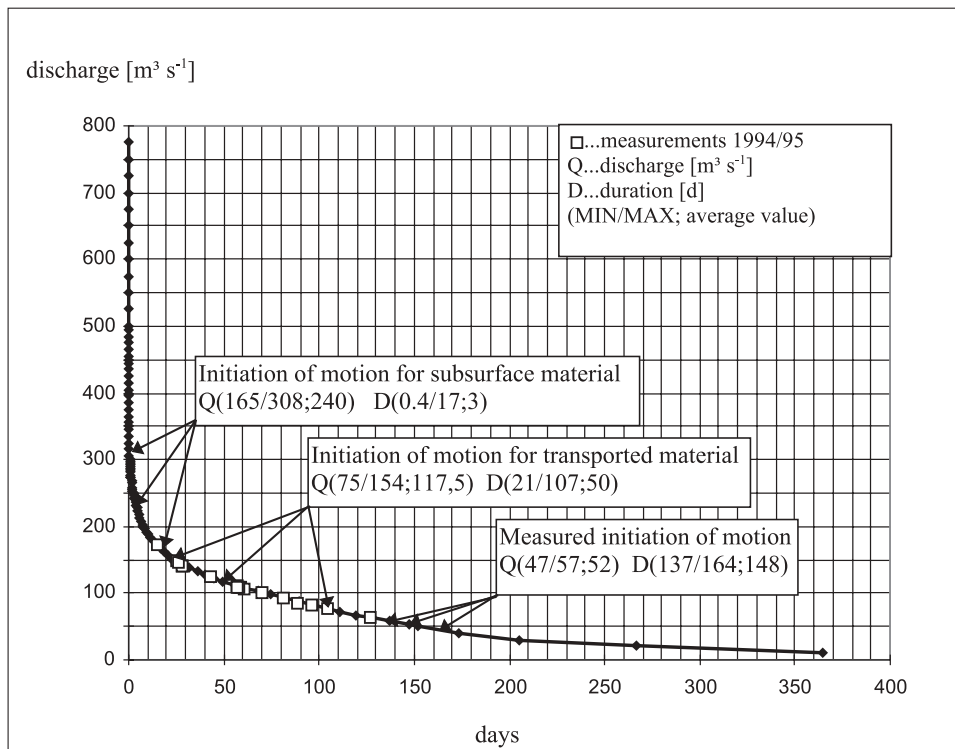


Fig. 7. Discharge duration curve (for 1969-1990), theoretical and measured values for initiation of motion of bedload in the Drau river

comparison with theoretical formulas of initiation of motion, the following relations were used:

- Meyer-Peter, Müller (1949):

$$\tau_{cr} = 0.047(\rho_s - \rho_w)gd_m = g \frac{Q_s}{Q} \left(\frac{k_{st}}{k_r} \right)^{3/2} h_{cr} S \quad (7)$$

- Shields (1936):

$$Fr_{cr}^{*'} = Fr_{cr}^* = \frac{\mu h_{cr} S}{\rho' d_{ch}} \quad (8)$$

Fr_{cr}^* = after Zanke, 1990 for a motion probability of about 10 percent.

- Hjulström (1935):

$$h_{cr} = \left(\frac{v_{cr}}{k_{st} S^{1/2}} \right)^{3/2} \quad (9)$$

the critical velocity can be derived from the Hjulström-diagram for critical velocities.

Zanke (1982)

$$v_{cr} = 2.8(\rho'gd_{ch})^{1/2} + 14.7 \frac{v}{d_{ch}} \quad (10)$$

$$h_{cr} = \left(\frac{v_{cr}}{k_{st} S^{1/2}} \right)^{3/2} \quad (11)$$

where ρ_w, ρ_s are respective fluid and sediment density, τ_{cr} is critical shear stress, d_{ch}, d_m are characteristic grain diameters, Q and Q_s are respective discharge and sediment discharge, h_{cr} is the critical water depth, S is the slope, k_{st}, k_r are respective the Strickler and grain roughness values, Fr_{cr}^* is critical Froude number, v_{cr} is

critical flow velocity, μ is a ripple factor, $\rho' = (\rho_s - \rho_w) \rho_w^{-1}$, ν is kinematic viscosity.

Critical water depth and critical discharge were calculated for initiation of motion with these equations (Table 1). The definitions of initiation of motion are not totally and mutually consistent among equations 7-11. However, the definition of initiation of motion is in itself a scientific feat, commonly within a wide range of values. For example, it was recently documented that the original Shields measurements include a large number of inconsistencies regarding initiation of motion (Buffington, 1999, Buffington & Montgomery, 1997).

Taking acceptable formulas for the calculation of the initiation of motion using grain sizes of the subsurface material, about 58 percent higher water depths are required in comparison to actual measured values. The use of transported material for the grain size leads to a better fit with measurements. Even here the duration curve (Fig. 7) shows that bedload (based on slot measurements) is initiated at $47 \text{ m}^3 \text{ s}^{-1}$, which occurs 137 days per year. Using the lowest theoretical critical discharge ($75 \text{ m}^3 \text{ s}^{-1}$), bedload transport occurs merely during 107 days per year.

Temporal variability

The temporal variability of bedload flux on a 1 hour interval basis is shown in Fig. 8. It can be seen that bedload waves occur with distinct peaks up to a maximum of $0.064 \text{ kg m}^{-1} \text{ s}^{-1}$.

An autocorrelation analysis demonstrated that a significant 24 hour period exists for the one hourly data. Statistically, the sediment flux peaks are measured around 0:00, varying between 22:00 and 03:00, whereas no transport occurs during the day around noon. One explanation for this situation is that a significant surge effect acts in the River Drau, leading to a 0.15 m daily variation in the water level. Because shear stress is close to the critical shear stress during this period of the year, the small increase in discharge (and water depth, as shown in Fig. 8) is sufficient to initiate weak bedload transport.

The correlation between bedload transport and water level is not significant, although a time-shift of the data by 8 hours increases the correlation, especially for the first 5 days (Fig. 9). This im-

Table 1. Initiation of motion: comparison of values derived from theoretical equations based on subsurface bed material with values derived from Helley-Smith and trap measurements.

	h_{cr} [m]	gauging station [m above ref. level]	Q [$\text{m}^3 \text{ s}^{-1}$]
Meyer-Peter/Müller (1949)	2.06	1.53	197
Shields, R=10% (1936)	2.41	1.90	252
Shields, R=0.2% (1936)	1.63	1.08	134
Hjulström (1935)	1.93	1.40	177
Zanke (1982)	1.99	1.46	186
measured with HSS	1.13	0.48	57
measured with trap	0.95	0.40	47

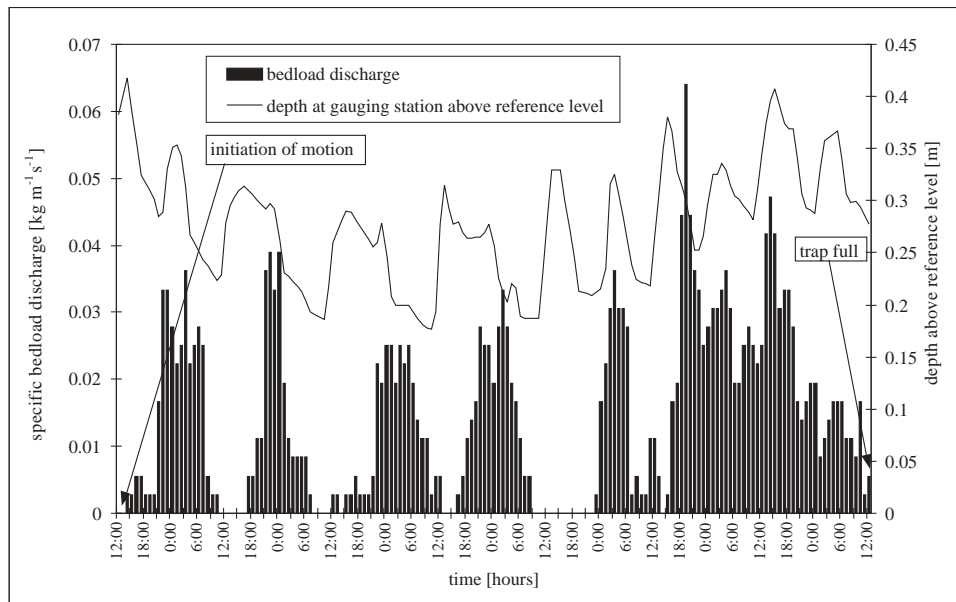


Fig. 8. Temporal variability of bedload transport over a period of seven days at the Drau River during spring, 1995.

plies that local hydraulic conditions are not the only control of bedload at the measurement site. In comparison to equilibrium conditions, which occur during floods at the river Drau, the armor layer was not broken, so that there was transport of fine bedload from upstream over the existing river bed. Our interpretation is that finer sediment may derive from the alluvial fans of upstream tributaries and that a certain travel time is necessary to transport the bedload to the measuring site. Additionally, water depth is self-evidently not the only bedload predictor; we anticipate further research in order to identify adequate predictors based on stochastic considerations. A survey of the riverbed along tributar-

ies and upstream of the slot should provide relevant information concerning the sources of bedload.

Conclusions

Several advantages of slot measurements compared to the basket sampler results have been identified for Alpine gravel bed rivers:

- automatic and continuous measurement of bedload transport over longer periods of time,
- accurate determination of initiation of motion, and
- detection of the temporal variability of bedload.

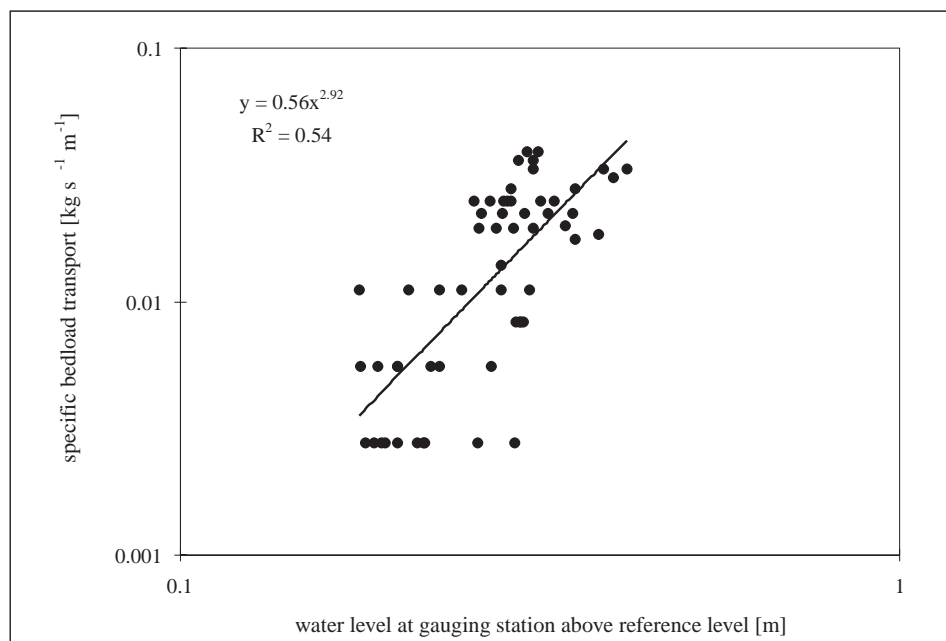


Fig. 9. Correlation between bedload transport and water level at the Drau gauging station for an 8 hour time difference.

Based on this experience, similar slot samplers may be used for automatic and continuous bedload transport measurements at other Alpine rivers. A survey of the river bed upstream of the measuring site will enable evaluations to be made concerning bedload supply and measured bedload flux.

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Notations

d	grain size and d_a as grain size for $\eta = 1$
$d_{ch,m,50}$	characteristic grain diameters
Fr^{*7}	Shields parameter by Shiquiang and Renn (1987)
Fr_c^*	critical Froude number
g	acceleration due to gravity
h_{cr}	critical water depth
k_{st}	Strickler roughness value
k_r	grain roughness
m_t	trapped bedload discharge
m_n	bedload discharge occurring in nature
Q	discharge
Q_s	sediment discharge
S	slope
v^*	friction velocity
v_i	average flow velocity inside the trap (on top of the trapped material)
v_o	average bottom flow velocity outside the trap (on top of the river bed)
v_{cr}	critical flow velocity
μ	ripple-factor (Bauer, 1965)
η	hiding Factor (Day, 1980)
ν	kinematic viscosity
ρ_w	fluid density
ρ_s	sediment density
ρ'	relative density
τ_{cr}	critical shear stress

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