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Analysis of sediment transport developments in relation to human impacts

HELMUT M. HABERSACK & HANS P. NACHTNEBEL
Institut für Wasserwirtschaft, Hydrologie und konstruktiven Wasserbau, Universität für Bodenkultur, Nussdorfer Lände 11, A-1190 Vienna, Austria

Abstract The objective of this paper is to analyse the long-term development in river degradation processes in a section of an Alpine Austrian river. Due to human impacts, such as river training works, gravel mining in the main river, torrent control structures in tributaries, both the bed load transport capacity and consequently the river morphology have changed. The collected data refer to longitudinal low water level measurements dating back to 1886, to detailed river bed monitoring of cross sections, grain size distribution of sediments obtained from several tons of samples and to gravel extraction data. Unfortunately, no sediment transport measurements are available. It can be concluded that the rate of degradation is substantially caused by gravel mining and by river channelization. The effect of sediment trapping in tributary basins can be seen in the longitudinally varying rate of degradation. This analysis should provide a basis for the redesign of the cross sections to reduce the degradation process in the long term.

INTRODUCTION

Rivers are very effective transport agents, which, through associated erosional and depositional activity, are responsible for changes in the morphology of river systems (Hey, 1987). However, human impacts have serious short and long-term effects on river morphology and sediment transport.

Despite the increasing economic importance of erosion, sediment transport and sedimentation, there are still very few data from long-term detailed monitoring programmes; this situation is unlikely to change in the near future given the current economic climate (Olive & Rieger, 1992). Changes in sediment transport have often been caused by engineering measures undertaken during the last century. These have lead to degradation problems in many Alpine rivers (Hunziger, 1991; Jäggi, 1992; Nachtnebel & Habersack, 1993).

River training works resulted in the long-term in an increased sediment transport capacity, while sediment trapping in the tributary basins has reduced the sediment input into the main river. Consequently, the bed load regime was substantially modified and degradation processes became dominating (in the long-term). A similar development was observed along the River Drau, located in the southern part of Austria. To maintain river protection works against scouring, increasing efforts had to be undertaken in the last decade.

The aim of this paper is to analyse the development of sediment transport in relation to human impacts, regarding spatial and temporal variabilities within a long river reach.

The analysis of the sediment budgets should assist in the development of economically justified and ecologically sound river management strategies.

STUDY REACH

The study reach is part of the River Drau (Fig. 1), which enters Austria in eastern Tyrol and flows to Slowenia. There are two dominant geological units in the catchment which are separated by the Drau: the Central Alps in the north (granite, gneiss) and the lower limestone Alps in the south.

Concerning sediment transport, and especially bed load supply, the Central Alps in the north (including the highest mountain in Austria and some glaciered areas) supply the most resistant sediment. Thus, they are quite important for the sediment transport and armouring processes in the study reach of the Drau. In comparison to the other tributaries, the River Isel, draining a large area in the central Alpine region, has the greatest influence on the sediment regime.

Hydrological data for the Drau in the study reach are given in Table 1. The distribution of the seasonal discharge is dominated by the contribution from glaciers, with minimum in winter and a maximum in June/July. Discharges above 300 $m^3 s^{-1}$ cause flooding, covering the whole valley, which is densely populated in several reaches.

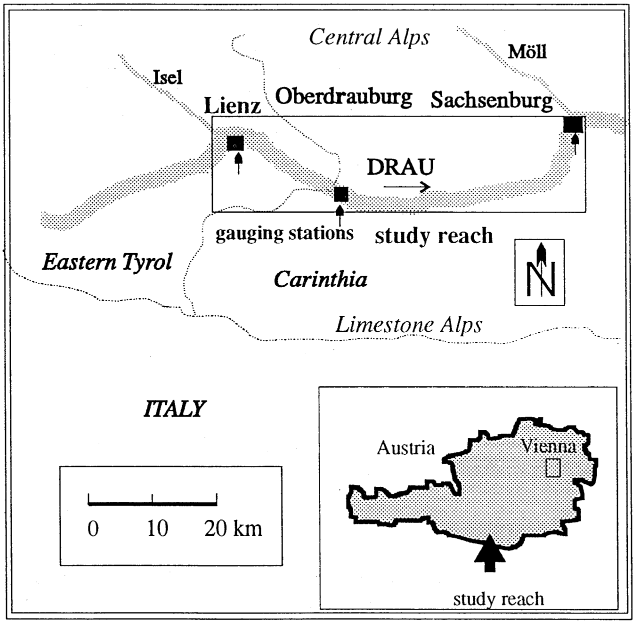

Fig. 1 Study reach at the River Drau in Austria.

Human impacts

Historical maps show that prior to 1890 the Austrian part of the River Drau was characterized by a large sediment supply from the Alpine sources. This resulted in a

Table 1 Hydrological data for three selected sections of the Drau.

Gauging station	Lienz	Oberdrauburg	Sachsenburg
Location (km)	0	15	57
Drainage basin (km^2)	1876.2	2112	2561.4
Slope (m m^{-1})	0.0025	0.002	0.0015
Channel width (m)	30	30-40	40-50
Average flow (m^3 s^{-1})	55	65	76
Q_{30}, HQ_{100} (m^3 s^{-1})	632; 760	706; 854	840; 1029

braided, aggrading channel system. Hence, one hundred years ago engineers were required to find solutions that would reduce aggradation and, particularly, the risk of flooding. At that time the reduction of channel width and bank protection measures were regarded as appropriate solutions to stop aggradation.

From 1890 to 1930 the river was channelized to a constant, uniform channel width of 30-50 m, resulting in a 34% reduction of the previous braided area. Because bed aggradation ceased and flooding was reduced, the engineering methods seemed to be successful. After 1930, and especially after 1965/1966, when high floods occurred, further regulations, bank protection measures and torrent control structures in 19 small sediment transporting tributaries were erected. These measures, the establishment of water power plants and gravel mining, affected sediment transport and river morphology. Adverse ecological developments, such as lack of dynamic gravel bars, decreasing ground water level and reduction of "Aue" areas, as well as interruptions of the river continuum have to be observed.

DATA BASE FOR SEDIMENTS AND MORPHOLOGY

The data base includes the following elements:

(a) maps dating back to 1820;
(b) annual longitudinal low water level measurements beginning in 1890;
(c) annually repeated cross sectional measurements since 1991;
(d) data from water authorities of the Drau and its tributaries;
(e) data concerning gravel mining; and
(f) grain size distribution of subsurface material.

Maps from 1824 and 1880 depict the river reach before regulation measures were installed. Annual low water measurements began in the late 1890s and annual longitudinal profiles are available for the Carinthian part of the study reach since 1931, with exception of World War II and 1965-1967. Low water (November until February) measurements at a 200 m spacing show the temporal development of the river bed as a consequence of sediment transport.

These results can be compared to repeated annual measurements of 14 cross sections, undertaken since 1990, and regression analysis of low water level developments at the gauging stations and river bed developments at bridge piers. Gravel

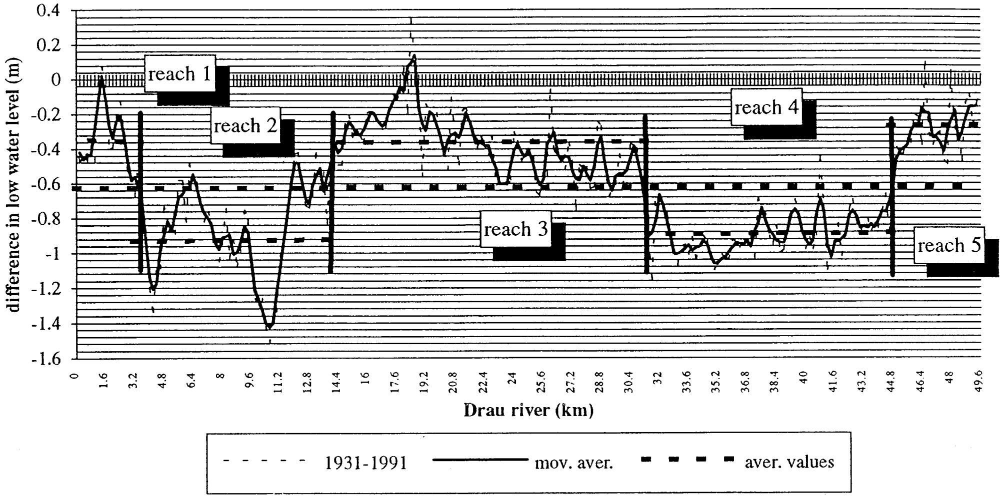

Fig. 2 Spatial variability of bed level developments at the Drau.

mining data and results of sediment analysis are compared with low water measurements to identify the different influences.

ANALYSIS OF SEDIMENT TRANSPORT

Spatial variability

Analysis of annual low water level measurements for the period 1931-1991 shows that the river bed degraded at a mean rate of 1.0 cm year^{-1}. Maximum degradation was 1.53 m (Fig. 2). Had a degradation rate of 1.0 cm year^{-1} occurred throughout the whole reach, the suggestions for further engineering methods would be not difficult. Volumetric comparisons between gravel mining and variations of the bed level showed that 60% of the changes were caused by gravel mining. In principle it can be concluded that gravel mining should be prohibited. At a few locations a surplus in sediment deposits after major floods would temporarily be available for gravel mining.

An obvious division of the Drau River in the Carinthian section into five separate, significantly different river reaches can be suggested in terms of the -0.6 m average degradation rate of the whole reach (Fig. 2). Reaches 1, 3, 5 have lower mean degradation rates (−0.32 m, −0.35 m and −0.28 m respectively), whereas reaches 2 and 4 are characterized by higher mean values (−0.95 m and −0.87 m).

Comparison of cross section measurements for the years 1990 and 1991 demonstrates that 66.9% of the whole river reach degraded, and 33.1% aggraded. This could be interpreted as reduction of the degradation tendency, evident from the low water level measurements, where 96% degraded, only 3.6% aggraded and 0.4% remained in equilibrium.

Regression analysis shows that low water level changes at the three gauging stations correspond with the low water level measurements at 200 m increments, as well as with changes of bed level observed near bridge piers. Hence, the whole analysis is highly accurate.

Besides these measurements, mathematical calculations and the application of simulation models allow the analysis of the present situation, and the prediction of developments of the river bed. For the River Drau, the bed load transport rate was calculated with the Meyer-Peter & Müller (1949) formula. In eastern Tyrol there exist levees on both sides of the Drau, which allow a flood control for HQ_{100}, whereas in Carinthia already floods of HQ_1 to HQ_5 inundate the whole valley. These different engineering methods affect the sediment transport rates (Fig. 3). In Carinthia, the transport rate corresponding to a discharge below 330 $m^3\ s^{-1}$ is higher than that in eastern Tyrol. The transport rate is then rapidly stabilized at 600 $m^3\ s^{-1}$ because of the large flood plain areas in Carinthia. For the transport rate in eastern Tyrol this point is reached at a discharge of 900 $m^3\ s^{-1}$, when levees are already flooded.

Grain size analysis of the subsurface (volumetric samples) has demonstrated that the mean diameter in reaches with large degradation is less than that of equilibrated or slightly degraded reaches. In places this is due to small tributaries in some reaches transporting coarser material to the Drau, creating an armouring layer. In reach 2 the mean diameter of the subsurface material varied between 22 mm and 26 mm, in reach 3 between 32 mm and 33 mm, in reach 4 *c.* 20 mm and in reach 5 *c.* 33 mm. The application of the formulae of Gessler (1965) and Günter (1971) demonstrate that in the whole reach of the River Drau there is a strong tendency for armouring.

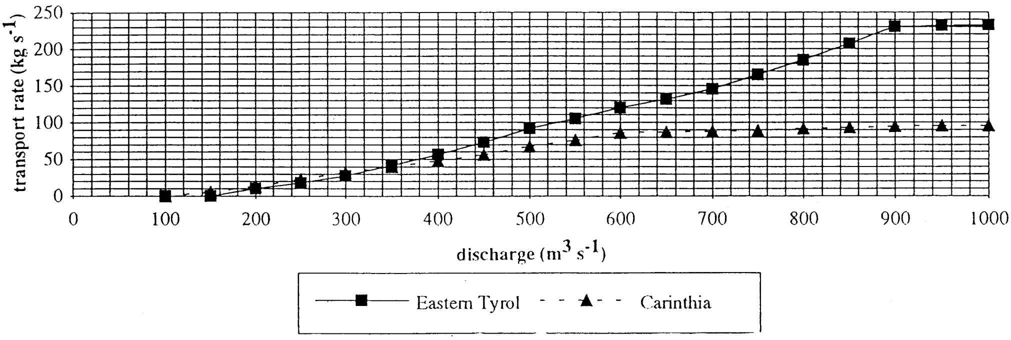

Fig. 3 Bed load transport rates at two different sites for the River Drau.

Temporal variability

The reason for taking 1931 to 1991 as a reference time period, in order to look at spatial variability of bed level changes, is that the largest engineering measures were already established by 1931, and afterwards stable conditions would have been ideal from an engineering point of view. In order to determine detailed temporal developments of the bed changes we have split the whole period into three subperiods (Fig. 4). The period 1931-1960 was characterized by tendencies for aggradation in reaches 1, 2, 3 and 5, whereas in reach 4 degradation occurred. From 1960 to 1969 reach 2 was especially affected by a large degradation rate of 1.5 m maximum. Most of the bed underwent degradation in reaches 1, 3, 4, 5. The larger degradation in reach 2 was caused by further regulation measures to protect a village after the catastrophic floods of 1965/1966.

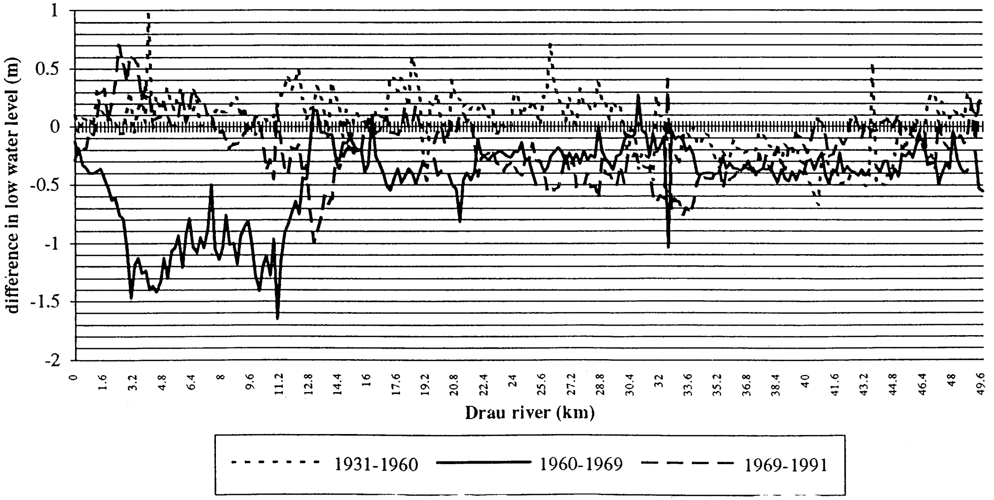

Fig. 4 Changes of low water level for different time periods.

By comparison 1969-1991 shows nearly opposite conditions in reach 2, with aggradation rates almost 0.6 m, whereas reach 3 was again more stable; reach 4 degraded up to 0.7 m and reach 5 slightly degraded. It is important to stress, that viewing just a certain period of time (for example 1969-1991) may lead to incorrect interpretations and conclusions with regard to the need for future engineering measures.

It is interesting to note, that since 1886 mean bed level changes for short periods of time show a rapid change between aggradation and degradation (Fig. 5). For the period 1886-1906 the mean value of bed level change was more than 0.15 m over the whole 50 km reach. Such aggradation was typical for this time period, as the whole reach was dominated by aggradation, before regulation measures were realized. Until 1914

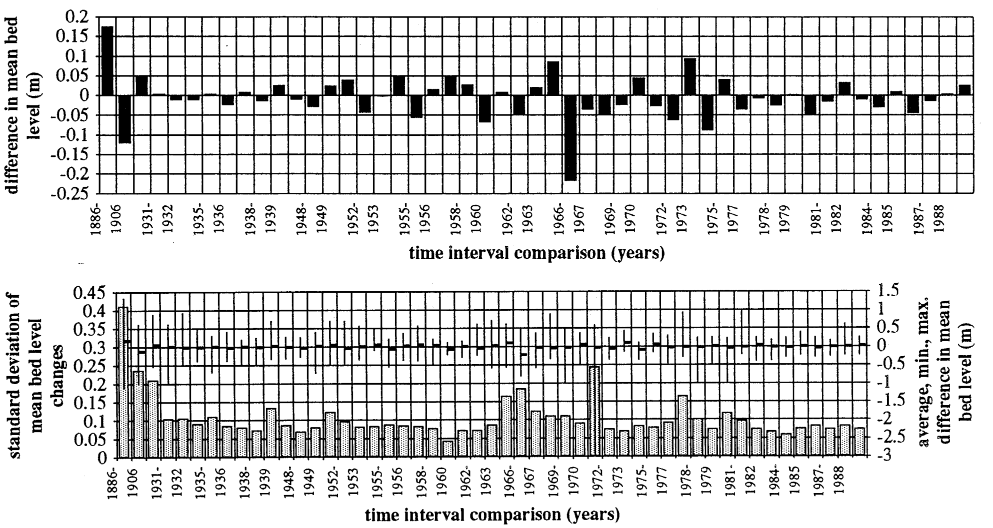

Fig. 5 Average bed level changes for time interval comparison within a time period from 1886 to 1993.

degradation was dominant. This had lead to the conclusion, that the engineering measures were successful.

Following this there were periods with aggradation as well as degradation but in general, degradation was dominant. The years 1965-1967 appear to have had the greatest influence for the period which followed. The big floods of 1965/1966, with 100 year discharges led to aggradation, immediately followed by considerable degradation from 1967. This prompted further regulation measures and gravel mining. During *c.* 15 years there was a situation comparable with the 1930s, perhaps with higher degradation rates. Minimum and maximum differences in low water level are now mostly within ±0.5 m, whereas formerly they were much larger. The very high standard deviation at the beginning of the century can be explained through the aggrading system that, with engineering measures, was transformed into a slowly degrading one in a relatively short period of time. Higher degradation rates were typical because of the introduction of engineering measures after 1965/1966.

When planning engineering measures for a management project it is crucial to consider the temporal and spatial variability in detail in order to evaluate river complexity. The time dependant development of special locations along the whole reach of the River Drau can be seen in Fig. 6. Some of the graphs are interrupted because of missing data for some years. Whereas at km 0.4, the difference between 1964 and 1969 is not significantly high, other locations downstream had degradation rates of almost 1 m. Downstream of km 16, this dramatic change cannot be observed and also the long-term degradation rate is not significant. Regression analyses show significantly high degradation rates over a period of more than one hundred years further downstream of km 16 and upstream of km 45 (Fig. 7). The lowest locations also show degradation, but not so significantly.

The reasons for the different behaviour of these river reaches might be found in the varying mean diameters of subsurface material, sediment input through small tributaries

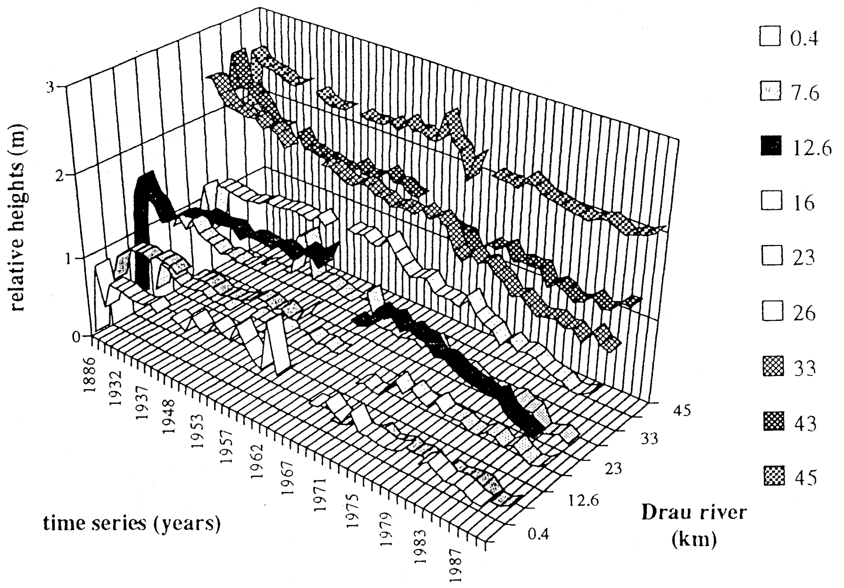

Fig. 6 Temporal and spatial variability of low water level developments at selected locations of the River Drau.

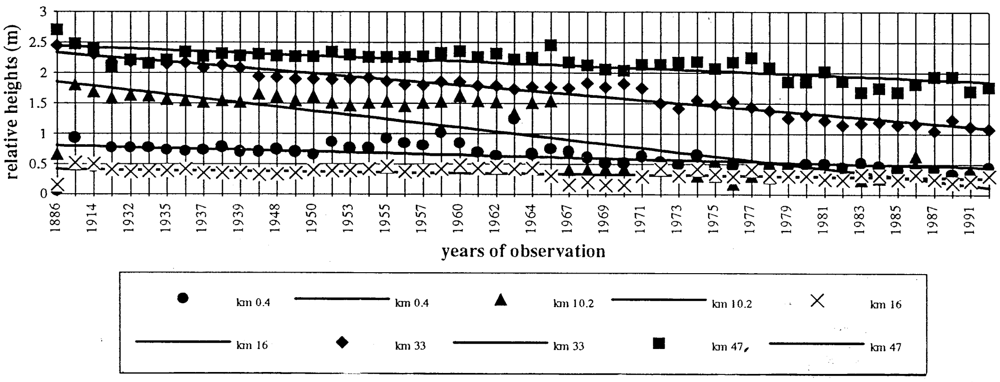

Fig. 7 Regression analysis of long-term river bed changes at different locations.

along the whole reach, selective transport, grain sorting, armouring effects and gravel mining. Selective transport is determined for the River Drau by downstream fining. Abrasion might be negligible, as Parker (1992) showed for quartz one of the main rocks transported by the tributary Isel. One important reason might be that a large amount of the transported sediments is deposited at the upper part of the reach and, therefore, further downstream there is a lack of material. This can also be noted in Fig.6, where aggradation takes place for the aggradation period 1886-1906 only until km 16, whereas downstream degradation occurs except for the last few kilometres.

CONCLUSIONS

The River Drau in Austria has problems related to the instability of bank protection measures and ecological deficits. The analysis of the data for a 50 km long reach of this river leads to the following conclusions:

(a) There is a definite relationship between sediment transport and human impacts.
(b) The uniform design of the cross sections is not appropriate to maintain a stable dynamic river bed.
(c) The volumetric amount of degradation corresponds to 60% of gravel abstraction.
(d) The input from small tributaries is important for the longitudinal changes in the river bed. Sediment input from these tributaries into the main river is mainly caused by local rainfall processes. Thus short term data describe local phenomena.
(e) To apply simulation models to rivers with variable beds, long-term observations are required and initial results indicate that such models can be applied for the River Drau.
(f) Short term data sets cannot reveal changes in of river morphology over long distances.
(g) Low water level measurements appear to be a cheap and fast method for monitoring bed level changes especially for long river reaches.
(h) Many closely spaced measuring points are more important for the analysis of sediment transport developments in relation to human impacts than only a few, daily measured ones.

(i) Detailed longterm monitoring programmes, including the whole drainage basin are necessary to explain sediment transport variability thereby allowing sound engineering design. A working group was established to plan and perform a future monitoring programme for the River Drau.

(j) The complexity of managing such rivers is determined by the large temporal and spatial variability of sediment transport.

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REFERENCES

Gessler, J. (1965) Der Geschiebetriebbeginn bei Mischungen untersucht an natürlichen Abpflä-sterungserscheinungen in Kanälen. *Mitt. der Versuchsanstalt für Wasser und Erdbau, ETH Zürich, Nr. 69.*

Günter, A. (1971) Die kritische mittlere Sohlenschubspannung bei Geschiebemischungen unter Berücksichtigung der Deckschichtbildung und der turbulenzbedingten Sohlenschubspannungs-schwankungen *Mitt. Nr. 3 der VAW der ETH Zürich.*

Hey, R. D. (1987) River dynamics, flow regime and sediment transport In: *Sediment Transport in Gravel-Bed Rivers* (ed. by C. R. Thorne, J. C. Bathurst & R. D. Hey), 17-40. John Wiley, London.

Hunziger, R. (1991) Flußmorphologie. *Modelle in der Geomorphologie* – Beispiele aus der Schweiz. Fribourg.

Jäggi, M. (1992) Sedimenthaushalt und Stabilität on Flußbauten. *Mitteilung VAW Zürich* **119**.

Meyer-Peter, E. & Müller, R. (1949) Eine Formel zur Berechnung des Geschiebetriebs, *Mitteil-ung aus der Versuchsanstalt für Wasserbau und Erdbau an der ETH-Zürich Nr. 16.*

Nachtnebel, H. P. & Habersack, H. (1993) Erhebung von gewässermorphologischen Daten – Auf-wand im Verhältnis zur Aussage. Stand der Technik im Landschaftswasserbau. **14**. *Seminar Landschaftswasserbau an der Technischen Universität Wien*, 147-177.

Olive, L. J. & Rieger, W. A. (1992) Stream suspended sediment transport monitoring – why, how and what is being measured? In: *Erosion and Sediment Transport Monitoring Programmes in River Basins* (ed. by J. Bogen, D. E. Walling & T. J. Day) (Proc. Oslo Symp., August 1992), 245-254. IAHS Publ. no. 210.

Parker, G. (1992) Some random notes on grain sorting. In: *Grain Sorting Seminar* (Centro Stefano Franscini, Monte Veritá Ascona, Switzerland), 19-76.