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SUSPENDED SEDIMENTS IN STREAMWATER – INDICATORS OF EROSION AND BED LOAD TRANSPORT IN MOUNTAINOUS BASINS

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ABSTRACT Two adjacent mountain streams draining small basins of different and variable land use (forests, pasture, wetlands) in the northern Prealps of Switzerland are compared with respect to suspended sediment transport. Four years data (1986-89) from continuous flow proportional but also irregular instantaneous sampling for suspended sediments in streamwater is analyzed. Even though the weather pattern is very similar in the basins, the suspended sediment regimes show marked differences: The Vogelbach basin (No. 3) with a generally more stable channel, with less slope failures reaching the channel and with deeper soils and a higher forest percentage shows a mean suspended sediment yield of 7250 kg ha^{-1} $year^{-1}$. The Erlenbach basin No.10 (12 250 kg ha^{-1} $year^{-1}$) however shows a considerably higher suspended sediment yield. The presence of a channel often on loose material, more eroded slopes bordering the channel and shallow soils with less forests seem to be the main reasons for the surprisingly large difference in suspended sediment yield. The bed load measurements from the sediment basin installed at the gauging site of Erlenbach is in reasonable relationship with the estimated suspended sediment load. Careful thought is also given to the methods and instruments with which the results have been obtained.

INTRODUCTION

Suspended sediment usually has a negative effect on water quality. In order to improve water quality the right measures should be taken, based on a knowledge of conditions which cause suspended sediment transport. Today our knowledge of the factors influencing suspended sediment transport in mountainous streams is limited. Therefore, the following questions need to be asked: What is suspended sediment? How does it originate? What are the roles of weather factors, soil, channel and slope conditions, vegetation and land use condition?

The erosional material in suspension in a river or stream is normally considered as suspended sediment. In mountainous areas, however, its size varies considerably with hydraulic conditions, turbulence, velocity, gradient, transport capacity and other stream features. This makes sampling and evaluation of the true amount of suspended sediment in torrent streams very difficult. For practical reasons we have therefore dealt only with fine materials of a diameter of less than 1.25 mm. This is an important limitation in this analysis.

Measuring suspended sediment continuously is difficult. We attempt to do it with an appropriate sampling scheme in order to document seasonal as well as annual variations in the stream as well as being able to compare two streams with respect to their suspended sediment yield. We are uncertain about the representativeness and rely therefore more on variations and differences, rather than on the absolute amounts of suspended sediment transported from each of the study basins.

There is much literature on suspended sediment (e.g. Walling, 1977; Truhlar, 1978; Griffith, 1982; Ferguson, 1986; Iroumé, 1990) but few studies have been conducted in steep, mountainous areas in sufficient detail to define the links to the stream and basin characteristics. Also for modelling, good basic knowledge of the processes is essential (Fleming & Fattorelli, 1986) to produce reasonable predictions.

THE STUDY SITE

Two small basins, located in the northern Prealps of central Switzerland are considered in this study. They are part of a long-term forest hydrology research project in several small catchments of the Alptal Valley. The geology is the Flysch formation, a tertiary sediment deposit affected by alpine uplift and faulting. Calcareous sandstones are intermittent with argillite and bentonite schists. The weathering of these bedrocks results in primarily fine, but also blocky material. Their delivery to the channel is strongly dependent on the stability of the land surface and particularly on stream erosion activity. The two basins are located only 4 km apart and show generally the same geologic and climatic background (Keller & Weibel, 1984).

The climate is cool with a mean annual air temperature of about 4.5°C, and annual precipitation totals of between 2000 and 2300 mm, of which up to 35% can fall as snow. In summer thundershowers with high intensity rain often result in high flood peaks. Annual evapotranspiration losses are estimated to be between 300 and 700 mm depending on soil conditions and plant cover.

TABLE 1 The main characteristics of the Vogelbach (3) and Erlenbach (10) basins in the Alptal.

	Vogelbach (3)	Erlenbach (10)
Area (km^2)	1.55	0.70
mean elevation (m.a.s.l.)	1365	1350
mean slope (%)	41	30
Forest area (%)	65	40
Pasture area (%)	10	-
Wetlands (not forested) (%)	25	60
mean annual precipitation (mm)	2050	2300
mean annual streamflow (mm)	1460	1850

The soils are of variable depth, often shallow and wet, high in clay content and with limited storage capacity. The drier sites are used for agriculture, mainly pasture along the ridges and on south facing gentle slopes. Forests generally cover about 50% of the land, but locally on a basin scale it ranges from 20 to 90%.

The two chosen research basins (see Table 1) in the area are also subject to various forest hydrology studies, including water balance, deposition and nutrient budgets on a basin scale.

The period used in this study extends from 1986 to 1989. For this period automatic continuous flow-proportional sampling supplemented by occasional instantaneous sampling was available for both basins.

METHODS

Instantaneous suspended sediment samples were taken irregularly when the streams carried clearly visible sediment. A 100 ml PE bottle was used and filled at a turbulent point generally near the middle of the stream.

To obtain the flow-proportional samples the following sampling scheme (the same as for streamwater chemistry) was used: At the gauging site a small portion of the flow is diverted into a bypass immediately to the side of the measuring channel. In this bypass water temperature and electrical conductance of the water are continuously recorded and water samples are pumped to the gauge house. A 1.25 mm monofil polyester (PES) mesh is placed at the intake to the 12.5 mm inner diameter tube leading to the sampler. The sampler consists of a control unit providing proportionality to streamflow using the water level and the rating table for estimation of streamflow. The other unit is the vacuum pump, the dosing installation and the 15 l composite sample container placed in a refrigerated box. The elevation difference between the bypass and sampler is 2.5 and 3.5 m at the two sites respectively. Most of the time the controller is set in such a way that for every 100 m^3 of discharge a discrete sample is taken. During low flow conditions (~8 l s^{-1}) at least 4 to 6 samples a day are secured, and for high flows not more than one sample per minute should be taken. This may become limiting during peak flows, since a pumping cycle lasts about 40 seconds. A flow rate of 2.5 m^3 per second calls for a sample every 40 seconds. Individual sample size is 10 ml, which allows up to 1500 samples to be taken to fill the sample container. The individual samples first pass through a bag (10 by 14 cm) of monofil polyester (PES) mesh (0.03 mm mesh size). Only the very fine material flows into the composite sample container. Every week the PES bag is changed and a subsample of up to 100 ml of the composite sample is taken by constantly stirring the sample water with a kitchen stirring equipment. Additional samples are then taken for chemical analysis.

In the laboratory the PES bag is dried over night at 95°C and weighed. The suspended sediment samples are filtered through a 0.8 µm filter dried for 2 hours at 75°C and weighed for later calculation of the combined suspended sediment concentration of both bag and filter.

In order to have a complete data set available for the comparison, a few missing data had to be estimated from concentration / streamflow relations for the preceding and subsequent periods. Also some corrections were necessary due to the malfunctioning of the automatic sampling equipment. During the 4 year period, less than 5% of the data were either missing or had to be corrected.

Very simple computational methods were used. The loads (kg ha^{-1} $week^{-1}$) were calculated as the product of concentration (mg l^{-1}) and streamflow (mm $week^{-1}$). Dividing by a factor of 100 allowed the conversion to kg and ha. A conversion of the weekly loads to the dimensions of g s^{-1} km^{-2} is also used for ease of comparison. Seasonal and annual loads were then obtained by summation. In the literature manual sampling and / or calibrated continuous turbidity measurements are often used to determine suspended sediment loads (e.g. Walling, 1977; Truhlar, 1978; Ferguson, 1986). Other methods are rarely found and whether proportional sampling is to be recommended has yet to be shown. If a true non-point source behavior in the basins can be assumed, the flow-proportional sampling is expected to yield reliable results, however if point source behavior prevails, the results would have to be viewed with caution. Our observations on soil and streambank erosion as well as on slope failure near the channel are at this stage of the study inadequate to judge this situation.

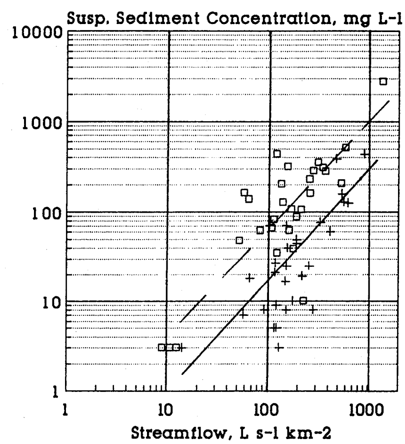

FIG. 1 Suspended sediment concentration C and streamflow Q in the basins 3 (+) and 10 ( ), Alptal: The instantaneous sample regressions are:
3: $C = -3.07\,Q^{1.22}$ $r^2 = 0.57;\ n = 29$
10: $C = -1.02\,Q^{1.15}$ $r^2 = 0.69;\ n = 30$

RESULTS

Instantaneous samples

Of primary interest is the variability of suspended sediment concentration and its relation to unit area streamflow. Figure 1 shows the scatter and the obvious differences between the two basins. The use of a rating curve to estimate concentrations from streamflow would be coupled with considerable error (Walling, 1977; Ferguson, 1986). Therefore no estimates of seasonal or annual loads are presented here.

Flow proportional samples

Weekly flow-proportional composite samples are in theory representative of the total suspended and dissolved solids passing the point of measurement assuming that non-point source conditions prevail. During high flows the sampling is frequent, low flow sampling at intervals of several hours, however, may miss substances passing the gauging site. Even though this sampling integrates a week of hydrologic history, the relation between flow and

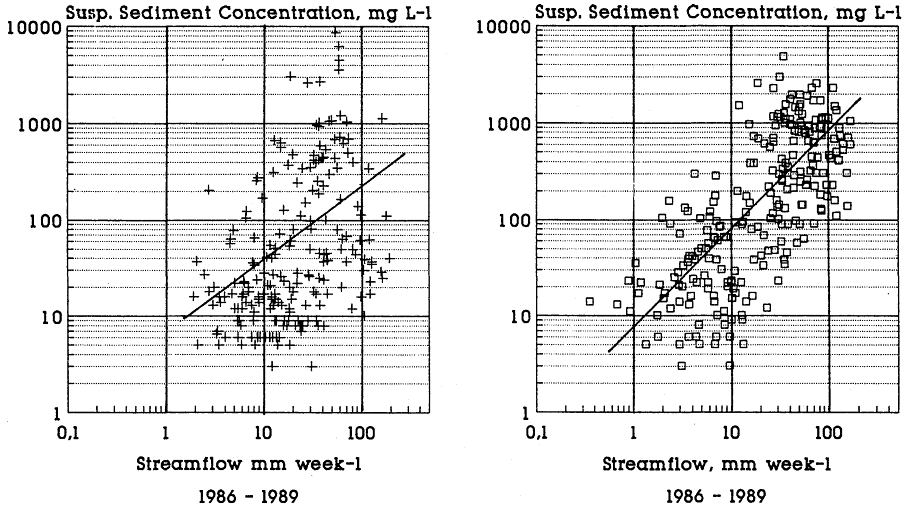

FIG. 2 Suspended sediment concentration C and streamflow Q in basin3 (left) and 10 (right), Alptal. The weekly flow proportional sample regressions are:

3: $C = 1.67\,Q^{0.71}$ $r^2 = 0.18$ $n = 209$

10: $C = 2.08\,Q^{0.93}$ $r^2 = 0.47$ $n = 209$

suspended sediment concentration (see Fig. 2) in the two streams still shows much variation. The hydrologic behavior of an entire week is reflected in each data point, but it is still difficult to explain the scatter. We note that the highest weekly concentrations do not occur with highest streamflow volumes, and similarly the lowest concentrations. But how can this be explained? At this point it seems therefore difficult to derive rating curves from these scatter diagrams to estimate suspended sediment loads.

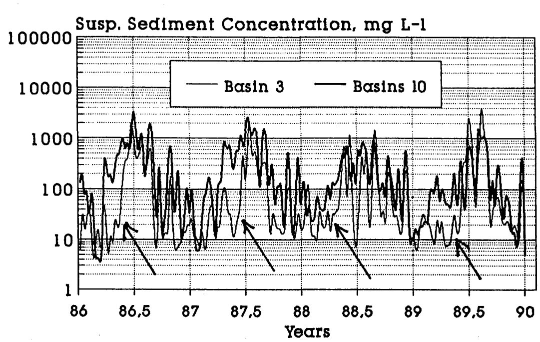

FIG. 3 Suspended sediment concentrations from weekly continuous sampling in basin 3 and 10, Alptal. Smoothed lines show seasonality. Note log scale and the differences during spring snowmelt (see arrows).

The seasonal pattern shown in Fig. 3 indicates, that in the spring, during snowmelt, the Erlenbach concentrations are higher than in the Vogelbach. During the summer the differences are less pronounced. The variation at low concentrations should not be viewed in detail, since concentrations of less than about 50 mg l^{-1} can be regarded as negligible. The seasonal pattern and the difference between the two basins is even more pronounced looking at the monthly loads in Fig 4. Only July and August, the months of typical thunder storm activity, result in similar suspended sediment loads.

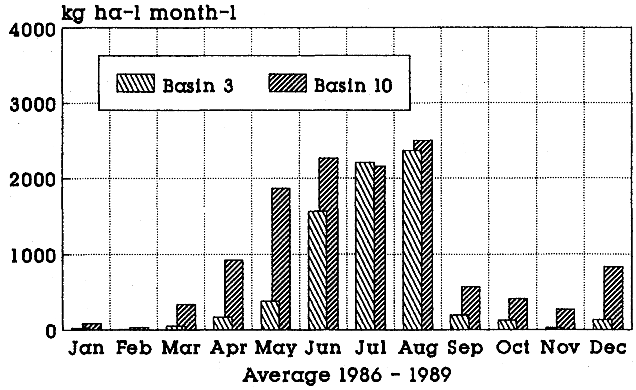

FIG. 4 Mean monthly suspended sediment loads for the period 1986 - 1989 in the basins 3 and 10, Alptal

TABLE 2 Frequencies of flow (from continuous records), suspended sediment concentrations and suspended sediment loads (both from weekly records) in basins 3 and 10 in the Alptal.

Parameter	Basin	Parameter exceeded during indicated percent of time 5%	50%	95%
Flow ($l\ s^{-1}\ km^{-2}$)	3	280.	20.	5.0
	10	340.	20.	2.5
Weekly suspended sediment concentration ($mg\ l^{-1}$)	3	1058.	27.	6.
	10	1546.	138.	6.
Weekly suspended sediment loads ($g\ s^{-1}\ km^{-2}$)	3	100.	1.	0.08
	10	200.	7.	0.05

Explaining differences

The flow and suspended sediment regimes of the two basins have been characterized in Table 2. The flow regime in the two basins is basically similar except for low and high flow frequencies. Vogelbach 3 shows higher low flows and lower peak flows than Erlenbach 10. Much greater differences are shown by the suspended sediment frequency. Both show similar concentrations at the 95% exceedence level (low flow, little disturbance). At the 50 and 5% level, however, the concentrations are considerably higher in Erlenbach 10 and the weekly loads are also as expected generally higher than in the Vogelbach basin.

TABLE 3 Annual and total suspended sediment loads in the basins 3 and 10, Alptal, 1986 - 1989, based on weekly flow proportional samples.

	Basin	1986	1987	1988	1989	86 - 89
Average weekly susp.	3	227	199	295	408	283 ±906
Sediment conc. mg l^{-1}	10	533	548	293	273	411 ±615
Annual susp. Sed.	3	4700	6700	6900	10 700	7250
loads kg ha^{-1} $year^{-1}$	10	15 400	18 800	7900	6900	12 250

It is not easy to explain the observed differences. Routine statistical analysis has proved inconclusive. But looking at the catchments more closely and beyond the parameters given in Table 1, in particular at soils and vegetation as well as at the stream channels and side slopes, we note the following differences: The main channel of Vogelbach 3 is for more than 50% of its length on bed rock or stable blocky material, mostly calcareous sandstones. Loose material with underlying schists, and eroded and undercut side slopes are rare in the lower half of the channel but frequenting the sections at higher elevations. The soils are relatively deep in the lower portions and more wet and shallow at higher elevations within the basin. The Erlenbach channel in contrast is situated only in a few places (less than 10% of its length) on stable blocks or on bedrock. For more than about 60% of its length the channel is unstable. The side slopes are frequently undercut and tend to move to the channel in an almost continuous motion. Fallen trees and logs block the channel and create temporary and limited stability. The soils are shallow throughout most of the basin and extended wetlands tend to destabilize the moist slopes near the channel.

Since direct point observations on water balance components are often insufficient for basin comparisons we used the results of simulations with the model "Brook" (Forster, 1989). From these simulations we find that in basin 3, 44% of streamflow is classified as so called surface flow (direct runoff), in basin 10, however, the proportion is 64%. In contrast the so called interflow (retarded runoff) is estimated to be 45% in basin 3, and 29% in basin 10. These results support the idea that the soil hydrologic behavior together with the channel conditions could be the main factors responsible for the different erosional behavior of the two basins. To show the link between soil moisture and suspended sediment concentrations in the streams, the period June 1986 through May 1987 has been used to combine the information on suspended sediment concentrations and simulated soil moisture. In Fig. 5 the typical seasonal behavior and in particular the abrupt change from variable summer episodes to rather stable winter conditions is seen. Recent winters with little snow however have shown less typical situations and the 4 year period 1986 - 1989 shows remarkable differences between years and between basins (see table 3). Instead of using rating curves, the load figures have been obtained by adding the appropriate weekly loads.

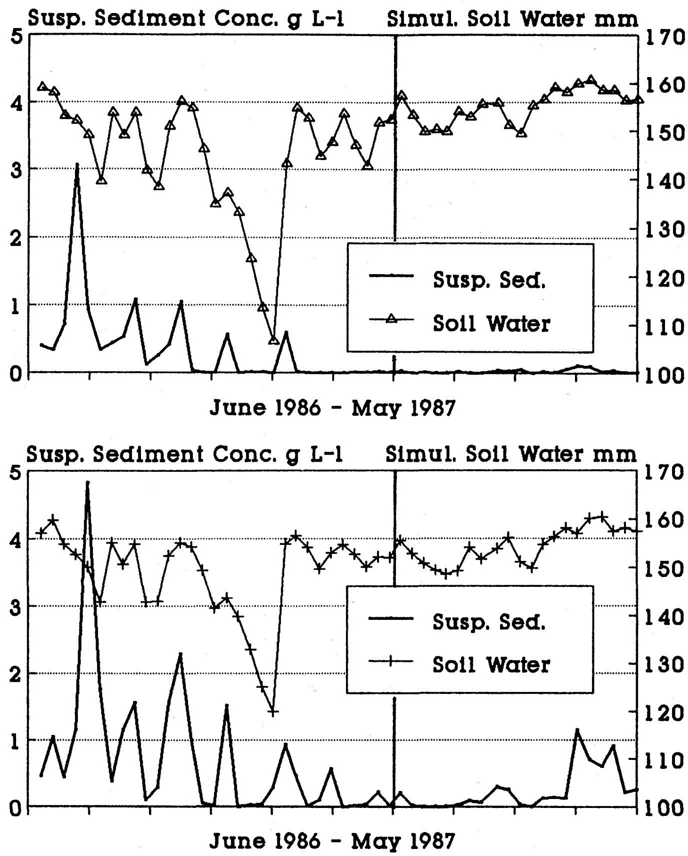

FIG. 5 Suspended sediment concentrations and simulated soil water in the root zone in basin 3 (above) and 10 (below), Alptal. Note that in winter snow cover reduces suspended sediment transport, even though soil water content in the root zone is relatively high.

Bed load and suspended sediment transport

The installation of a sediment basin at the outlet of Erlenbach 10 offers the opportunity to compare bed load transport as measured in the sediment basin with the suspended loads calculated from flow proportional sampling. Figure 6 shows that there is a relationship between the two and that it seems worthwhile to study the role of suspended sediment as an indicator of bed load transport.

CONCLUSIONS

Even though the analysis of a 4 year period with continued measurements of suspended sediment provided reasonable and plausible results, there is still uncertainty about the representativeness of the flow proportional sampling scheme. The observed differences between the two neighboring basins seem to be more reliable than absolute figures on concentrations and loads.

Combining field measurements, channel survey, simulation of flow components and soil moisture dynamics seems to offer a key to better understanding of suspended sediment transport in small, steep, mountainous basins. Further testing of observation methods and of suspended sediment and bed load transport processes in torrent basins is needed.

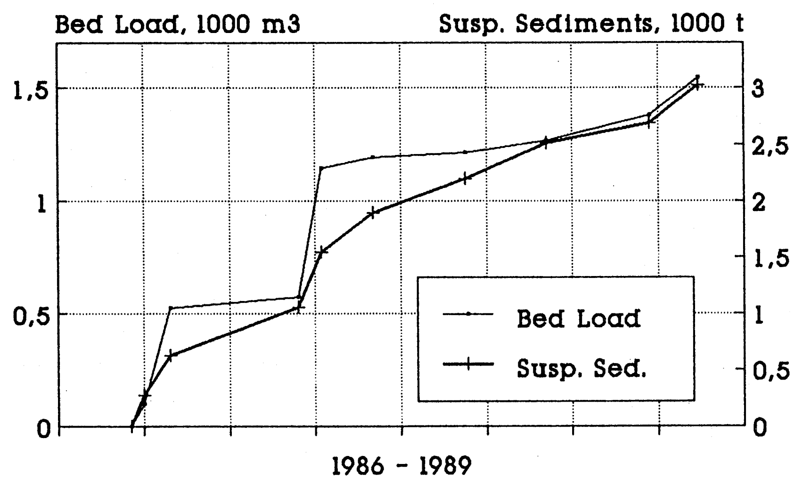

FIG. 6 Bed load and suspended sediment transport as determined at the gauging site of basin 10. Note that we do not know how much of the suspended sediment is passing through and leaving the sediment basin.

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