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Sediment transport observations in Switzerland

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Abstract A brief overview of sediment transport observations and the monitoring network in Switzerland is given. Some results of long-term observations point out seasonal, annual and long time variations of sediment transport, depending on climate and discharge. Chief emphasis is given to observations and problems in steep mountainous catchments. In addition some event related observations in alpine torrents are presented.

INTRODUCTION

Switzerland, situated in central Europe (41 300 km^2), is a mountainous country with most of its area located in the Alps. Switzerland varies geologically, topographically and hydrologically. Due to great differences in soil types, land use, and climate within a small area, there are considerable variations in the quantity and distribution of precipitation as well as a great number of different runoff regime types. From 1901 to 1980, the mean annual values of the water balance components of Switzerland are precipitation 1456 mm, runoff 978 mm, evaporation 484 mm, and the change in water reserves (lakes, reservoirs, glaciers, groundwater) − 6 mm. Flood discharge varies very widely in neighbouring hydrological basins, and causes great damage each year, e.g. in 1987 over 2 billion US dollars. In the northern part of the country, the maximum flood discharges are significantly lower than in the southern part.

The Alps, as a Tertiary mountain chain consist mainly of crystalline and sedimentary rocks with a wide range of different lithologies. The Swiss midlands, in contrast contain mainly tertiary strata which are deposits of early alpine erosion, and of a sequence of deposits of ancient seas and lakes. The northernmost geological region is formed of limestone rocks. The main flood problem originates in the Alps. Because of this, there is also great variation in sediment transport phenomena.

For the Swiss water management and environmental protection, a knowledge of the sediment potential and sediment transport by torrents and mountain streams, or deposition in reservoirs and lakes, is of vital importance. Sediment observations in Switzerland are primarily used for planning, design and the carrying out of flood and low water protection measures, for the solution of qualitative water protection problems, for planning of buildings and transportation routes close to waterways, as well as for basic research. The planning of stabilization measures for river beds and banks, the determination of the effects of torrents on their receiving waters, the planning of intakes, supplies and discharges, the isolation of danger zones, treatment of accretion problems and the planning of watershed management all require information on sediment transport.

OBSERVATION OF SEDIMENT TRANSPORT

Observations in torrents

Bed load discharge in torrents is only measured at two places in Switzerland with the aid of underwater hydrophones continuously. A bed load sensor is mounted on the bottom of a steel plate that is built into a check dam. Stones rolling over the plate cause vibrations which are registered by the sensor. The number of registered impulses per unit of time is a measure of the intensity of the bed load transport over the measurement cross section (Fig. 1). Additional long-term bed load measurement is made in bed load traps which have been set up throughout Switzerland (Fig. 2). As a result the bed load of specific flood events, the yearly bed load and the bed load transport over a period of several years can therefore be determined. After catastrophic floods, additional debris flow deposits outside the river course are measured.

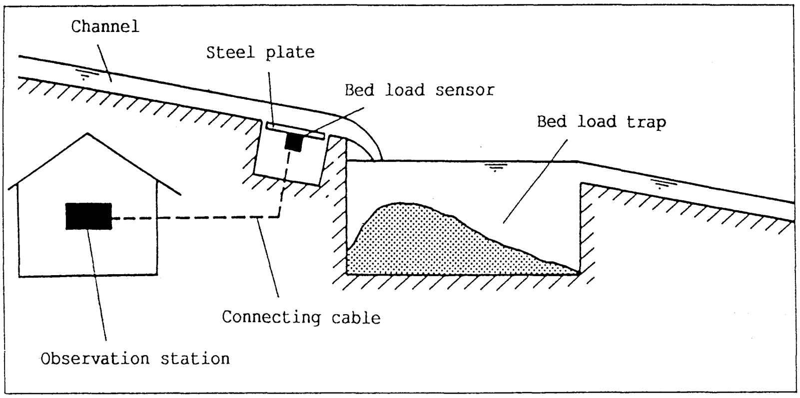

Fig. 1 Schematic diagram of a measurement station with installed hydrophones (WSL, 1993).

Observations in rivers

Bed load discharge is measured with the help of bed load samplers. It is also measured in sediment retention basins that are periodically emptied, in clearly defined dredging points and by analysing the deposits in reservoirs and lakes.

Suspended sediment concentration is measured using manual and automatic samplers. The suspended sediment load is then calculated using the measured suspended sediment concentration and the location specific relationship between the suspended sediment concentration and discharge.

Observations in reservoirs and lakes

Sediment input into reservoirs and lakes is recorded by means of periodic delta surveys. Sediment totals are estimated by measuring influents and effluents, as well as bathymetric observations in the reservoirs. The concentration of suspended sediments is measured by samplers, pumps and turbidity meters. The depth of deposited sediment

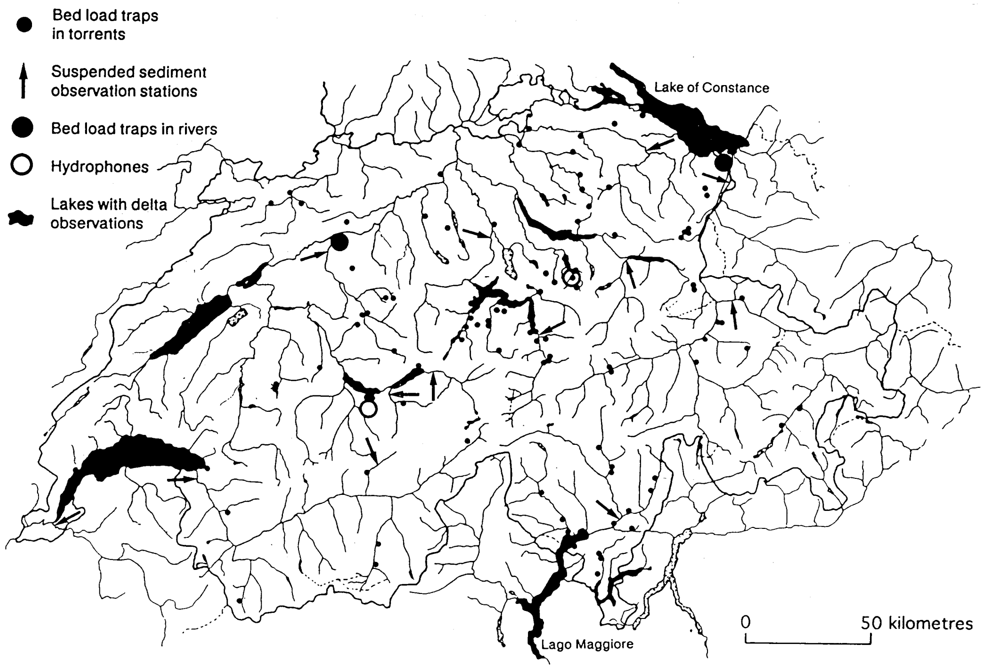

Fig. 2 Sediment transport observations in Switzerland.

layers per unit time is determined using sediment traps and sediment gauges (Fig. 2). In addition to these parameters, the grain size distribution of the bed load and suspended sediment, the grain size and petrography, as well as specific weights, are determined.

Crystalline rocks (granites, gneiss) and metamorphic and nonmetamorphic sedimentary rocks (rocks containing carbonate such as limestones, sandstones) strongly influence the water composition of the River Rhine and its tributaries.

The solute (chemical) erosion is influenced by weathering processes. The annual solute erosion rates in the mountainous parts of the Rhine basin are smaller than the mechanical rates while in the lower Rhine the opposite occurs (Table 1).

LONG-TERM OBSERVATION

Observation of deltas

Despite error in delta surveys the data can be used to gain insights into the behaviour of rivers and the erosion in their drainage basins. The intensity with which a given watershed is eroded is mainly dependent on its original natural state (geological structure, weathering, precipitation and discharge, vegetation and soil conditions, etc.), and on the impact of human activities upon this system (agriculture, forestry, water management, waterway channelling, raw material mining, slope stabilization, etc.). Where the receiving water of the watershed is stationary, as in a lake, these factors then determine the growth of the corresponding delta.

Table 2 presents delta measurements from the Maggia in Lake Maggiore. Calculations of the mean of the average annual values from the periods 1926-1932 and

Table 1 Annual solute and mechanical erosion rates in the Rhine basin (Zobrist & Stumm, 1979).

River/Place	Altitude (m a.s.l.)	Total yearly quantity of minerals dissolved (g m^{-2})	Yearly quantity of mechanical erosion (g m^{-2})
Switzerland			
Hinterrhein/Hinterrhein	1584	50	<1000
Rabius/Safien	1220	260	<500
Landwasser/Alvaneubad	940	120	<1000
Rhien/Schmitter	410	206	470
Germany			
Rhien/Lobith (Lower Rhine)	11	208	28

Table 2 Results of delta surveys in Lake Maggiore (Lambert, 1988).

Delta	Catchment size (km^2)	Year of measurement	Period (years)	Average density of points (pts per km^2)	Volume of deposits (m^3)	Deposits per year: total (m^3)	Deposits per year: per km^2 catchment (m^3)	Denudation rate of the catchment (mm $year^{-1}$)
Maggia	926	1890		26				
		1926	36	330	19 840 000	567 000	612	0.6
		1932	6	508	1 002 000	167 000	180	0.2
		1952	20	720	4 900 000	243 000	262	0.3
		1984	32	1 276	10 400 000	325 000	351	0.4

1952-1984/85, yield a value of 246 000 m^3, which lies only 3000 m^3 above the mean of the intermediate period (1932-1952). From this it can be assumed that the intermediate period characterizes sediment transport under average meteorological conditions. On the other hand, the period 1926-1932 with its under average values, indicates a time period without large events, and the last period indicates a period of more intensive larger events.

The delta of the Rhine in Lake of Constance demonstrates a similar pattern. The long-term time series of the sediment input into Lake of Constance shows the strong relationship between both total load and suspended sediment transport, to discharge of the tributaries (Fig. 3). It can also be seen that the volume of transported sediment not only is influenced by flood discharge, but also by antecedent large flow events and anthropogenic impacts (such as dredging etc.).

The equipment and methods currently used for measuring sediment transport in Switzerland are described in Spreafico *et al.* (1984, 1987).

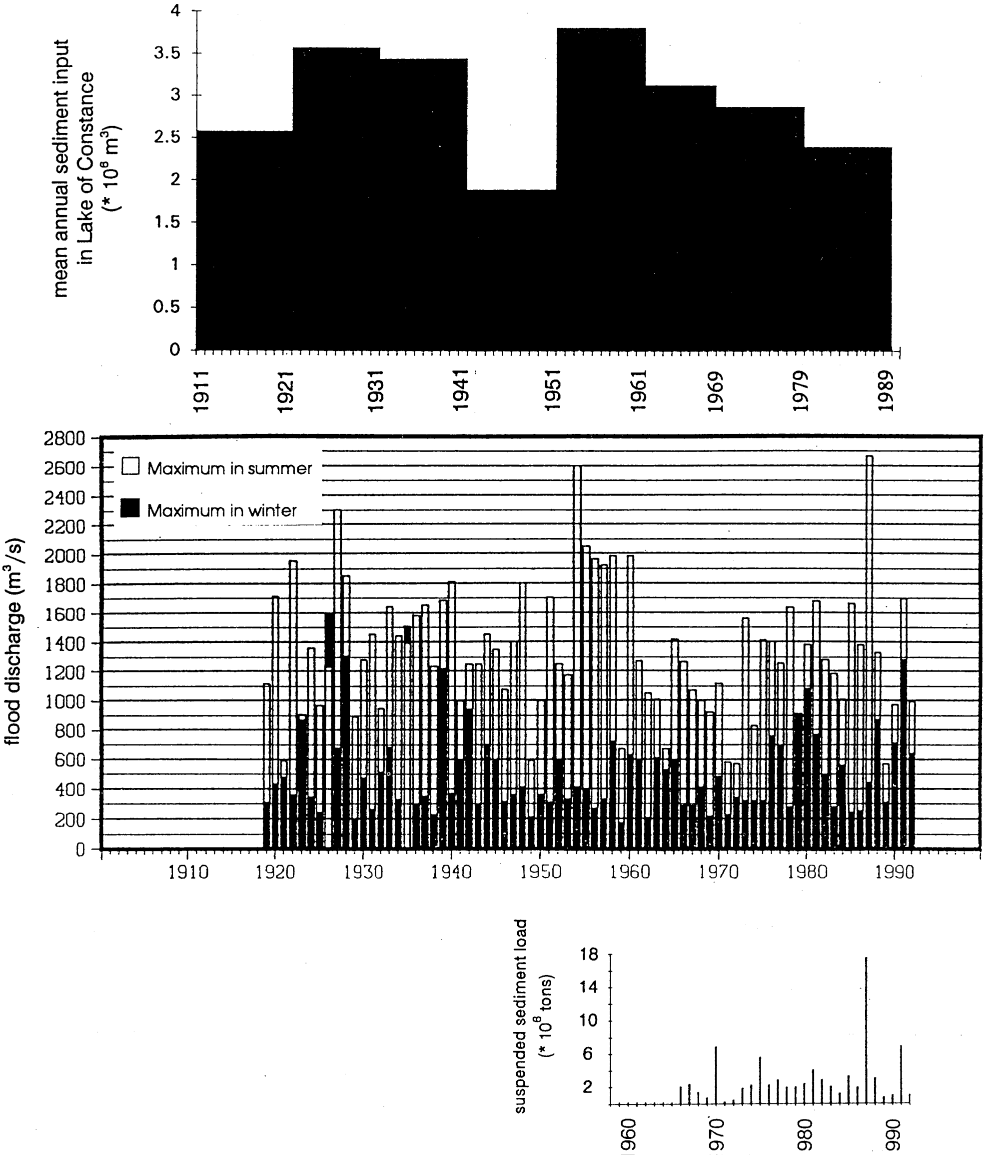

Fig. 3 Relationship between flood discharge and sediment input to Lake of Constance.

Observation of suspended sediment

Figure 4 shows the mean monthly suspended sediment loads of the stations Lütschine-Gsteig (1964-1993) and Thur-Halden (1975-1993). The graphs show the dependence of the transported sediment loads on the flow regime. The discharge of the Lütschine is largely influenced by glacial runoff where high discharges occur in summer, and a much larger amount of suspended sediment is transported. The Thur reflects a nival-pluvial flow regime without noticeably higher summer discharges, and therefore represents a more even suspended sediment transport behaviour over the whole year (Fig. 4).

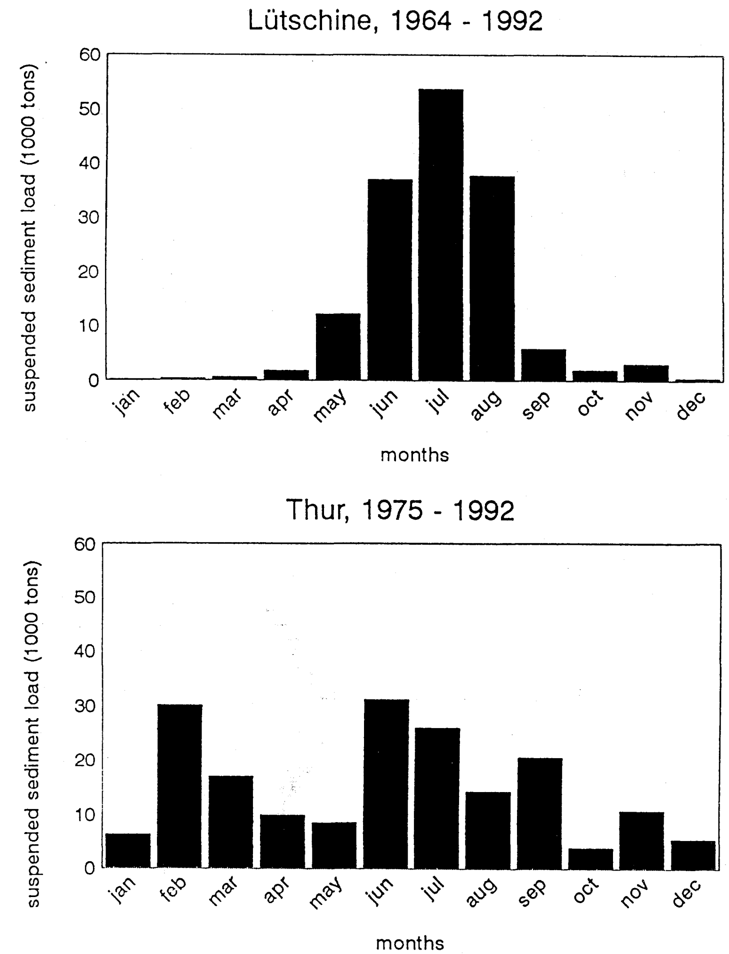

Fig. 4 Monthly suspended sediment load of different flow regimes.

EVENT RELATED DATA OF SEDIMENT YIELD

In Switzerland, sediment yields of extreme events have recently gained more attention. This was mainly due to increasing damage to settlements in the past few years, especially in the Alpine areas. In many cases the damage caused to settlements and cultural land is due more to debris flow rather than to water or suspended sediment. In fact, almost every year there are torrential sediment disasters affecting small villages and towns. In 1987, the small town of Minster in the canton of Wallis was seriously affected, and in September 1993 it was the town of Brig, Wallis, that suffered from a large torrential flood, which buried an important part of the town with sediment. Fortunately, this event claimed no more than two lives, but damage to the infrastructure amounted to some 500 million Swiss francs. In general only newly built up areas are damaged, but in the case of Minster in 1987, it was an old town. For centuries, no severe flood had been reported in the torrent "Minstigerbach". The event was partly a result of glacier retreat uncovering a large debris field, which was finally the starting zone of a debris flow.

Previously in Switzerland, the volume of sediment to accumulate from large events was only assessed or measured in exceptional circumstances. As a result, the sediment data of the extreme events presented here have been collected in the past two decades (Fig. 5). Accumulations of sediment was first measured or assessed after the large event in 1977 in the canton of Uri, central Switzerland. Since then, data have become more commonly collected. The events of 1987 induced progress in the collection and interpretation of torrential processes. Interpretation of sediment data are nevertheless a problem, because most data are not the result of measurements but mainly of assessments. They are based on various methods, like counting or weighing fully-laden trucks, measuring sediment retention basins or assessing eroded volumes in the basins.

For a better understanding of the processes that led to the 1987 disasters, the Swiss Federal government started a complete investigation of the various events. Studies on torrential processes (sediment budget, debris flows etc.; c.f. Bundesamt für Wasserwirtschaft/Landeshydrologie und -geologie, 1991) were especially stressed. Empirical studies of torrential processes, like debris flows, were carried out (Zimmermann, 1990; Rickenmann, 1990; Roesli & Schindler, 1990; Haeberli *et al.*, 1990; VAW, 1992). Also the role of sediment sources was studied, including the assessment of sediment budgets of large events in small Alpine catchments (Kienholz *et al.*, 1991).

Detailed investigation of some pre-alpine torrents showed that an important part of the total sediment volume is accumulated along the channel. It also showed the role of different sediment sources (Zimmermann *et al.*, 1988). Similar results in comparable alpine torrents have emerged as a result of the 1987 investigations (Kienholz *et al.*, 1991).

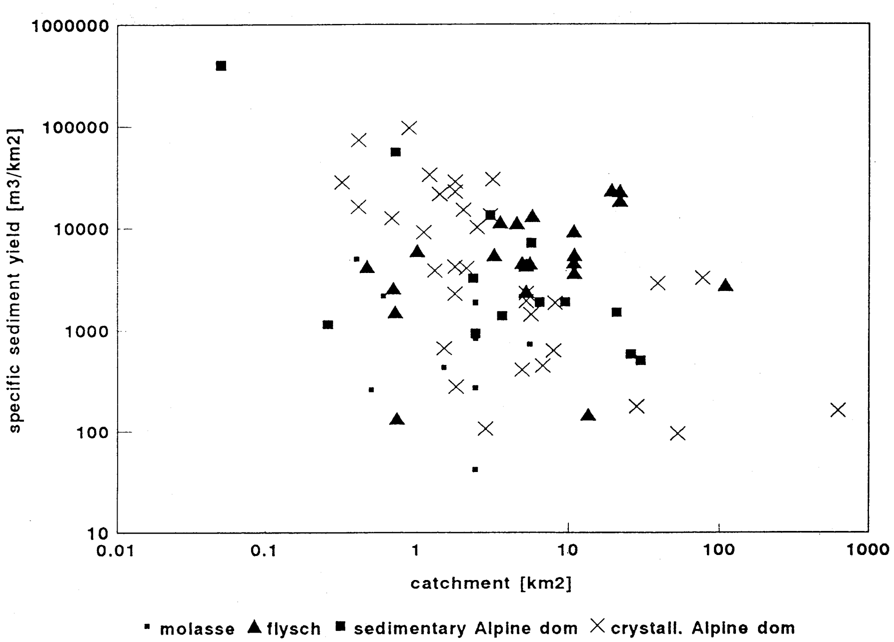

Fig. 5 Specific sediment yield of important events in torrents in Switzerland (Lehmann, 1993).

Figure 5 is a preliminary result of a collection of event-related sediment yields which have been carried out in the last few years. The data have been collected using a range of methods (e.g. obtained by measuring, interpretation from documents, assessment of accumulation etc.), but they show a decreasing specific sediment discharge with increasing basin size along the abscissa (catchment area). Four geological categories are distinguished (molasse, flysch, sedimentary Alpine domain and crystalline Alpine domain). The four categories represent the geographical regions "Mittelland" (molasse), the pre-alpine, (that is the area along the northern border of the Alps, corresponding to the flysch) and the Alps, including both categories, sedimentary alpine and crystalline alpine domains. In Fig. 5 it can be seen that on average the highest specific sediment yield appears in the flysch zone and in the crystalline alpine domain. Torrents in the flysch zone often show slope instabilities and easily erodible soil, while in the sedimentary Alpine domain it is often erosion resistant limestone rock that causes less material to be transported downstream.

In a few cases, a long time- series of event-related sediment volumes was obtained, as in the small catchment of the Schipfenbach, canton Uri (Fig. 6). Data like these allow the assessment of recurrence intervals of sediment discharge, and shows that high sediment volumes may occur frequently compared to medium-sized ones. Since these data are also the result of assessments (a sediment retention basin was only installed after 1977), time series like this can help planning for more accurate measurements to be made, and prevent future damage to infrastructure on the fan.

As already mentioned, an investigation of the 1987 events showed a wide variation of sediment discharge in torrents. This variation was due mainly to sediment transporting processes along the channel: debris flows may transport much higher

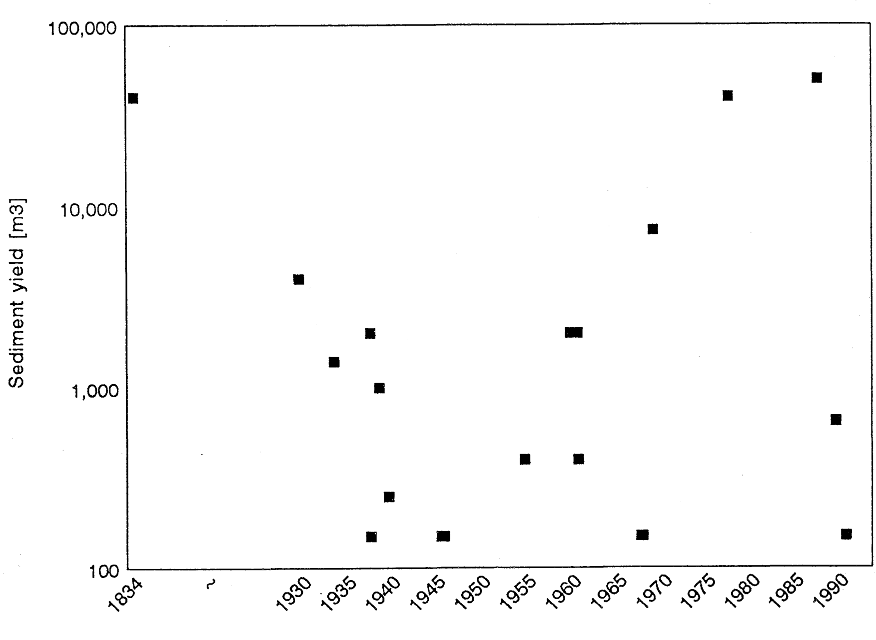

Fig. 6 Sediment yields of known events in the Schipfenbach, canton Uri, central Switzerland.

volumes than "normal" sediment transport. As shown in Fig. 5, geology also plays an important role, as well as the availability of erodible material along the channel.

The importance of the 1987 events with regard to long term erosion (due to geological relevance assumed as 10 000 years since the last ice age) can be shown in Table 3. Comparing the "mean annual denudation rate" to the "denudation rate" of the 1987 events, the one of the 1987 events is up to 40 times larger than the "mean annual denudation rate". Some events are of small geomorphological relevance only: the volume of the transported material may only correspond to the annual denudation rate. Denudation variations of the 1987 events however are also a function of geological effects that influence general fan growth (e.g. small growth rates in relative stabile limestone catchments). It is of course difficult to determine gross sediment output of a basin by measuring a fan, because of unknown losses of suspended material by washout. The other problem relates to the calculation of "mean annual denudation rate", mainly because of non linear fan growth since the last ice age.

Table 3 Denudation rates and sediment yield of some 1987 events in torrents in Switzerland (Lehmann, 1993).

Torrent	Volume of fan (000 m^3)	Basin size (km^2)	Specific yield per year (m^{-2} m^2 $year^{-1}$)	Denudation rate (mm $year^{-1}$)	Specific yield of the 1987 events (m^3 km^{-2})	Corresponding "denudation" of the 1987 events (mm)	Ratio of "denudation" 1987 to long-term denudation rate
Plaunca, GR	no fan	3.9	-	-	37 200	37.2	?
Minstigerbach, VS	13 161	15.4	85	0.08	2922	3.0	40
Zavragia, GR	14 169	13.3	106	0.11	4451	4.5	40
Sinzera, GR	13 546	3.9	347	0.35	3641	3.6	10
Ri di Cavanna, Tl	7 412	3.8	195	0.19	4526	4.5	25
Saxetbach, BE	8 843	20.7	43	0.04	1033	1.0	25
Ri Bassengo/ Croarescio, Tl	33 162	13.9	238	0.24	439	0.4	2
Rabius/Luven, GR	67 858	8.7	780	0.78	563	0.6	1
Ri di Ronco, Tl	5 841	3.0	195	0.19	4633	4.6	25
Geschinerbach, VS	7 750	5.5	141	0.14	654	0.7	5
Ri di Bedretto, Tl	7 454	4.1	182	0.18	195	0.2	1
Milibach, VS	10 838	3.8	285	0.28	342	0.3	1
Ferrera, GR	9 795	13.6	72	0.07	279	0.3	4
Dongia, Tl	1 698	7.0	24	0.02	157	0.2	10

CONCLUSIONS

In Switzerland, there are some reliable long time series of sediment data, but there is still an obvious deficiency in sediment measurement and data collection. This is especially the case in torrents and small mountain streams. In torrents, bed load transport is quite irregular, which means special instrumentation is required to get reliable results. Although there are continuous long term observations of bed load carried out in special catchments, data of event related sediment yields are still rarely collected. One of the main problems is that the collection of such data requires a dense measuring network which will not immediately yield results, because important torrential events are quite rare in Switzerland. It is yet not possible to measure sediment transport directly in torrents. There are some methods in use, but none of them are appropriate to operational application.

To obtain a better understanding of the various torrential processes, long term and event related observations have to be emphasized in the future. These might include specific evaluation of measurements from research stations, as well as reliable methods for measuring suspended sediment in small torrents. With respect to provide event-related sediment data, assessments of accumulated bed load volumes may be carried out besides continuous monitoring. More automatic measuring instruments for continuous monitoring should be used to determine suspended sediment loads in rivers. The extrapolation of random samples of suspended load concentration to sediment yields is very uncertain because of no direct relation to water discharge.

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