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Damage costs due to bedload transport processes in Switzerland

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Abstract

In Alpine regions, floods are often associated with bedload erosion, transport and deposition along the streams. These processes pose hazard in addition to the elevated water discharge. However, it is unclear to what extent they contribute to total damage caused by natural hazards. Using the Swiss flood and landslide data base, which collects financial damage data of naturally triggered floods, debris flows and landslides, we estimated the contribution of fluvial bedload transport processes to total damage costs in Switzerland. For each data base entry an upper and lower limit of financial losses caused by or related to bedload transport processes was estimated, and the quality of the estimate was judged. When compared to total damage, the fraction of bedload transport damage in the 40 yr study period lies between 0.32 and 0.37. However, this value is highly variable for individual years (from 0.02 to 0.72). Bedload transport processes have induced cumulative financial losses between 4.3 and 5.1 billion Swiss Francs. Spatial analysis revealed a considerable heterogeneous distribution with largest damage for mountainous regions. The analysis of the seasonal distribution shows that more than 75 % of the bedload damage costs occurs in summer (June–August), and ~ 23 % in autumn (September–November). With roughly 56 %, by far most of the damage has been registered in August. Bedload transport processes are presently still inadequately understood, and the predictive quality of common bedload equations is often poor. Our analysis demonstrates the importance of fluvial bedload transport as a natural hazard and financial source of risk, and thus the need for future structured research on transport processes in steep streams.

1 Introduction

World-wide, natural hazard events such as floods and landslides cause large financial damage every year. Most recently, MunichRe (2012, 2013) reported worldwide overall losses of 380 and 170 billion US$ for natural catastrophes in 2011 and 2012, respectively. Osterkamp et al. (1998) estimated that physical, chemical and biological damage due to movement and deposition of fluvial sediment in North America exceeded 16 billion US$ per year (base of 1992 dollars). Their estimates are based on literature addressing environmental and economic damage costs by fluvial erosion, sediment transport and re-deposition of material and sorbed contaminants. In Alpine regions, floods in torrents and steep mountain streams are almost always associated with sediment transport in form of debris flows and fluvial bedload transport. Thus, bedload transport represents a principal natural hazard in a mountainous environment (e.g. Rickenmann and Koschni, 2010). In the worst case, large flood events eventually lead to overbank sedimentation and deposition on alluvial fans, for example as a result of a rapid decrease in channel gradient along critical reaches (e.g. Jäggi et al., 2004). Especially where mountain streams draining large catchments (> 10–20 km^2) meet densely populated areas and infrastructure, the damage potential is considerable (Bezzola et al., 1994; White et al., 1997; Arnaud-Fassetta et al., 2005; Bezzola and Hegg, 2007; Totschnig et al., 2011). In addition, lateral erosion along stream banks often causes substantial financial damage during large floods (e.g. Waananen et al., 1971; Balog, 1978; Walther et al., 2004; Hunzinger and Durrer, 2008; Krapesch et al., 2011), sweeping away agricultural land, destroying roads and other infrastructure, and damaging buildings. Nitsche et al. (2011) estimated that fluvial bedload transport processes contributed a third to a half of the total financial damage in the severe August 2005 flood event in Switzerland, amounting to up to 1.5 billion Swiss Francs (CHF). Notwithstanding, we suspect that the importance of bedload transport processes is generally underestimated in a regional or national perspective. The assessment of damage costs over large spatial and temporal scales is important and provides a sound basis for the evaluation and definition of protection requirements of a national economy. Furthermore, fluvial erosion and deposition damage estimates could be helpful in assessing the degree of efficiency of existing protection measures.

Data on damage caused by floods, debris flows, and landslides have been systematically collected in Switzerland since 1972, and rockfall data since 2002.

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Information on natural hazard events affecting property values, infrastructure, forestry and agriculture is described and recorded in the Swiss flood and landslide damage database (Hilker et al., 2009). On average, damage costs amount to about 330 million CHF a year for the period from 1972 to 2011 (Andres et al., 2013). With approximately 90 million CHF the median value is considerably lower, which points to the significance of a few major events during this time. Database entries are assigned to one of three main categories. The vast majority of the costs (93.3 %) can be ascribed to flooding in the broad sense, including debris flows. The remaining costs split between landsliding (6.4 %) and rockfall (0.3 %). Of course, the quite coarse classification cannot comply with the multiplicity of potential natural hazard processes in Alpine regions. In particular, the category "flood/debris flow" does not differentiate between the actual flooding or inundation process by small streams, rivers or lakes and the erosion and deposition of material along a water channel. However, in general the provided information allows determining whether and to what extent fluvial erosion or deposition took place.

To the knowledge of the present authors the quantification of financial damage induced by fluvial erosion and deposition of bedload in torrents, streams and rivers has never been systematically undertaken. Here, we present a re-analysis of the Swiss flood and landslide damage database quantifying the fraction of financial losses related to bedload transport processes over a study period of 40 yr along water courses in Switzerland. As such, our study represents the first analysis of the spatial distribution of financial losses caused by bedload transport. The observed distribution is discussed by relating regional cost estimates to simple parameters describing the geomorphic characteristics of defined subareas.

2 Data and methods

2.1 Data on damage caused by natural hazards in Switzerland

Since 1972, estimates of the direct financial damage caused by naturally triggered floods, debris flows, landslides and (since 2002) rockfall events have been collected in the Swiss flood and landslide damage database (Hilker et al., 2009). The project is ongoing and at the time of writing the database comprises 40 yr of data. It represents the basis of the present study focussing on damage costs related to fluvial bedload transport processes. The structure of the Swiss flood and landslide damage database and the process of estimating financial damage are described in detail by Hilker et al. (2009). Here, we briefly recapitulate the most important aspects of the database and then describe the assessment of damage related to fluvial bedload transport.

The main source of information for the damage data is provided by approximately 3000 Swiss newspapers and magazines, scanned daily by a media-monitoring company. Additional information may be collected from insurance companies, public authorities and police or fire brigade websites.

For each community affected by a single natural hazard damage event, a dataset entry is generated. A dataset contains information on (i) the locality where damage was caused, (ii) date and time, (iii) the type of damage-causing process and secondary processes, (iv) the triggering weather conditions, (v) a description of the event, (vi) the number of fatalities, and (vii) the estimated direct cost of damage in the community. In some cases, damage cannot distinctively be assigned to a municipality; therefore the damage event is allocated to the affected canton. For a few cases where financial damage could not be assigned to a canton, a collective dataset entry was created.

A dataset entry describing a specific event is allocated to one of the main damage process categories flood/debris flow, landslide or rockfall. In this study we are interested in the category flood/debris flow, which includes the actual flooding processes by small streams, rivers or lakes (inundation) as well as erosion and deposition of material along a water channel. In many cases additional information is provided in the database, and secondary processes (such as overbank sedimentation and bank erosion) are indicated. The availability of such supplementary information depends on the detail and accuracy of the data source.

The direct financial damage in CHF is estimated according to the information sources, whereby the estimates are largely based on experience. Costs are associated with a certain type of affected object (Table 1 of Hilker et al., 2009). These object types are subdivided into three main classes: (i) "material assets" such as destroyed or damaged buildings, protection structures, vehicles, etc., (ii) "traffic lines/infrastructure" such as transportation routes, power-supply and telephone lines, and (iii) "forestry/agricultural land". While insured property damage costs and not-insured or not-insurable material damage costs (i.e. direct financial damage) are considered in the Swiss flood and landslide damage database, indirect losses, later reconstruction measures and intangible damage are not included. We provide damage costs in CHF in our contribution (value as at 15 July 2013: 1 CHF = 0.81 € = 1.05 US$) and take inflation into account for all financial data.

2.2 Estimation of damage caused by fluvial bedload transport processes

A river carries sediment in two different ways (Einstein, 1950; Vanoni, 1975): (i) as bedload when particles roll, slide or saltate along the channel bed or (ii) as suspended load when particles are supported by turbulent forces and move considerable distances without touching the channel bed. Whether a particle of a certain size is transported in form of bedload or suspended load depends on the hydraulic characteristics of a channel. Generally, with increasing catchment size and decreasing channel gradient, the threshold particle size for bedload transport decreases (Lamb et al., 2008). In the context of this contribution, we consider sand and coarser size fractions. We did not consider damage costs due to debris flows.

The Swiss flood and landslide damage database includes more than 19 000 single entries for the period from 1972 to 2011. Running a search for approximately two dozens of specific keywords related to fluvial bedload transport and channel erosion, we were able to reduce our working database to roughly 5000 entries in a first step. All these entries had to be screened separately in a second step. During this process, for each entry we had to decide whether fluvial bedload deposition or erosion played a substantial role in the damage symptoms or not; and in the former case, the financial damage induced by bedload transport processes was then estimated. For the estimation procedure, we decided to apply an upper and a lower limit of damage. In so doing we were able to specify the uncertainty regarding the determined damage cost by bedload erosion and deposition.

Because it is sometimes difficult to identify the exact natural hazard process in the database entries, we also introduced a possibility to assess the uncertainty regarding the described damage process. In the Swiss flood and landslide damage database, costs are associated with a certain type of affected object (see above and Hilker et al., 2009). For every existent estimate in a certain object type for which fluvial bedload erosion or deposition is held responsible, the certainty in terms of the underlying damage process can be evaluated. This is carried out by assigning to the estimate pair (lower and upper limits) a number from 1 to 3, termed process uncertainty index, where 1 = high certainty regarding damage cause and 3 = poor certainty regarding damage cause. For each entry a mean process uncertainty index is calculated by weighting the factors associated with the different cost estimates based on the absolute value of the estimate. Similarly, mean process uncertainties for entire damage events or years in the investigation period can be assessed.

Finally, we have provided the possibility to specify every estimate pair associated to any object type and ascribed to fluvial bedload erosion or deposition as “bedload-related damage” specifically. We define bedload-related damage as any damage that occurs because considerable bedload erosion or deposition made it possible. An example is damage caused by flood water after channel aggradation occurred on an alluvial fan. In this case the damage was made possible by a bedload-related process (channel aggradation), even though bedload was not directly responsible for it.

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2.3 Spatial presentation of the data

We used two spatial resolutions in this study to represent the distribution and variability of damage costs induced by bedload transport processes in Switzerland. In the damage database the data are acquired at municipal level. In Switzerland there are 2495 political municipalities (as of 1 January 2012), comprising areas ranging from 0.32 to 430 km^2. Municipal data were then combined into seven regions based on geomorphologic-climatic criteria (Fig. 1). Our approach rests on a subdivision used in avalanche warning by the WSL Institute for Snow and Avalanche Research SLF (2012). A total of 124 SLF warning regions were combined to form seven subareas that vary in elevation range, gradient and/or climatic influences: Jura, Swiss Plateau, Prealps, Central Alps, Valais (without the Chablais Valaisan), Grisons (without the Valle Mesolcina) and Ticino (together with the Valle Mesolcina) (Fig. 1). The main characteristics of the seven Swiss subareas are summarized in Table 1.

2.4 Determination of various geomorphological parameters in subareas

We characterised the physiographic properties of the seven subareas (cf. above) by the mean and standard deviation both of the absolute altitude and the channel bed gradient. These data were obtained from a digital elevation model with a spatial resolution of 10 m × 10 m . Channel bed gradients were calculated with standard flow routing algorithms for all streams that drain a hydrological catchment with an area of at least 0.1 km^2. In addition, the seven subareas were characterised by the spatially averaged precipitation and the population density (cf. Table 1).

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3 Results

3.1 Temporal distribution of bedload damage costs

From 1972 to 2011, fluvial bedload erosion and deposition has induced a cumulative financial damage between 4.3 and 5.1 billion CHF (Fig. 2), which is about one third of the total damage. Approximately 73 % of the cumulative damage costs caused by bedload transport processes affect the object types classified as "material assets" (e.g. destroyed or damaged buildings; cf. Sect. 2.1). One quarter of the damage costs is related to "traffic lines and infrastructure" and as little as 2 % of the losses are attributed to damage on "forestry and agricultural land". Annual losses due to fluvial bedload transport, just like total annual losses caused by all the natural hazard processes considered in the Swiss flood and landslide damage database (Hilker et al., 2009), vary considerably from year to year. We specified roughly 12–13 % of the cumulative bedload transport costs as bedload-related damage (550–630 million CHF).

The average annual cost of damage caused by fluvial bedload transport processes in the 40 yr study period lies between 110 and 125 million CHF (mean of yearly lower and upper estimates). The median value, however, is considerably lower (13–16 million CHF), reflecting the high variability in the annual damage data (Fig. 2). In years with very high to exceptionally high total costs (> 500 million CHF), damage costs due to bedload transport often also exceed the mean annual value. The two exceptions to this pattern are 1999 and 2007, two years strongly influenced by considerable floods in large Swiss rivers, such as e.g. the Aare River, mainly affecting the Swiss Plateau. During the other years with high total damage costs, the occurred bedload transport damage can generally be ascribed to one major event and is not the result of several small or medium events (cf. Sect. 3.3).

Damage costs caused by bedload transport processes are fairly evenly distributed over the four decades covered by the study (Fig. 2). This can be explained by the fact that at least one severe event, during which sediment transport played a crucial role, occurred in each of the decades. The upper estimates vary between 1028 million

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CHF for the decade from 1982 to 1991 and 1496 million CHF for the decade from 2002 to 2011, with a mean value of 1266 million CHF. Clusters of consecutive years with substantial bedload transport damage are rare. Three above-median years in a row are reported only once in the dataset from 1977 to 1979, showing a cumulated financial loss of approximately 1200 million CHF (upper estimates). Periods with very little damage costs induced by bedload transport are more frequent and occurred e.g. from 1972 to 1976, from 1980 to 1986 or from 2001 to 2004 (all below-average years).

The fraction of bedload transport damage compared to the total damage lies between 0.32 and 0.37 for the full investigation period. However, this fraction was highly variable from year to year (Fig. 2). While very low values below 0.05 are reported for the years 1973, 1988, 1994 and 2001, our estimations resulted in fractions of approximately 2/3 or more for the years 1978, 1979 and 1993. For single severe flood events such as the Brig sediment disaster of 24 September 1993 (cf. below Sect. 3.3 and Bezzola et al., 1994) the value exceeded 0.80. In contrast, the ratio of bedload damage costs to total costs does not vary considerably from decade to decade. The first decade of our dataset (1972–1981) shows the highest value of 0.48 (ratio calculated using the mean of the lower and upper estimates). In the following three decades the ratios amount to 0.31, 0.35 and 0.30, respectively.

The seasonal distribution of bedload erosion and deposition damage follows the distribution of the total damage costs according to the flood and landslide database, but its non-uniformity is even more accentuated (Table 2). Nearly all of the damage due to bedload transport occurs in summer (June through August, > 75 %) or in autumn (September through November, ca. 23 %). With roughly 56 %, by far most of the damage has been registered in the month of August. Financial losses in winter and spring combine to about 2 % of the total. As expected, the ratio of bedload transport damage to total damage falls in line with the absolute occurrence of bedload transport damage (Table 2). While the fraction lies below 0.10 from November to May, June represents a transition month with 0.11–0.14 (based on lower and upper estimates, respectively). In July, August and October the ratio amounts to roughly 0.40 and in

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September it reaches a maximum value with approximately 0.60, which can largely be ascribed to the Brig sediment disaster of 1993 mentioned above.

3.2 Spatial distribution of bedload damage costs

The spatial distribution of the cumulative damage costs caused by bedload erosion and deposition in the 40 yr from 1972 to 2011 is displayed at two different spatial resolutions: (a) at the municipal level (borders from 2011) according to the data acquisition in the Swiss flood and landslide database (Fig. 3), and (b) aggregated at the regional level (Fig. 4).

3.2.1 Municipal level

A high spatial variability in financial losses caused by bedload transport processes can be observed in Switzerland on the municipal level (Fig. 3). In general, medium and high cumulative costs are concentrated in mountainous regions (subareas 3–7). Only very few clusters of severely affected municipalities exist. Most communities with high cumulative bedload transport damage (> 50 million CHF, the top two classes in Fig. 3) are reported from the subarea of the 4-Central Alps (nine communities), followed by the 5-Valais and 6-Ticino subareas (each two communities) and the 7-Grisons and 3-Prealps subareas (one community each). Mostly, the majority of reported damage costs in a municipality occurred during one large event. In communities of the lowland subarea 2-Swiss Plateau and of the hilly 1-Jura subarea, cumulative damage costs in the 40 yr period do not exceed 12 million CHF and only a few municipalities have encountered considerable problems due to bedload processes there. Actually, many municipalities all over Switzerland have been exposed to very little financial losses related to bedload transport (or none at all), most of which are located in the Swiss Plateau and Jura. To a lesser extent, such untroubled communities also arise in southeastern Switzerland in the subareas of Grisons and Ticino.

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Within the Swiss Plateau, the northeastern and central parts of the subarea show more municipalities affected lightly or at a medium level than the southwestern part. In the latter part of the subarea, even lightly affected municipalities are scarce. Such heterogeneity within a subarea can also be identified in the Ticino, where the southern tail and some areas in the subarea center disclose smaller cumulative losses due to bedload transport. Like the Ticino, the Grisons subarea shows the entire range of damage classes within its municipalities, from places with virtually no bedload damage to places with very high damage (> 100 million CHF). Compared to the other mountainous subareas (Prealps, Central Alps and Valais) the spatial damage pattern of these two subareas is considerably more heterogeneous. This is also reflected by the percentage of municipalities affected by bedload transport damage during the 40 yr period (Table 1). Whereas many communities in the Prealps, Central Alps and Valais subareas encountered bedload transport problems over the years (> 72 %), the Grisons and Ticino subareas have a somewhat smaller percentage of affected communities (< 57 %).

3.2.2 Regional level

The total damage costs due to natural hazard processes (as reported in the Swiss flood and landslide damage database) and damage costs caused by bedload transport only are represented in Fig. 4, aggregated for the seven subareas and the entire 40 yr period. Total damage is highest for the Swiss Plateau subarea (ca. 3000 million CHF), closely followed by the Central Alps. Considerable total damage costs are also reported in the subareas Prealps, Ticino and Valais whereas the Jura and Grisons show noticeably lower values.

The cumulative damage costs solely induced by bedload transport processes are highest in the Central Alps (1310–1490 million CHF). While in the Valais and Ticino subareas the upper estimates also lie above 1000 million CHF, they amount to roughly 770 million CHF in the Prealps and to about 270 million CHF in the Grisons. Combined, the mountainous subareas (3–7) make up for more than 90 % of the financial losses

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connected to bedload transport processes. As mentioned above (see also Fig. 3), problems related to bedload are less pronounced in the Swiss Plateau and the Jura where cumulative financial losses of only approximately 240 and 25 million CHF were reported, respectively.

For every municipality, we normalized bedload damage costs with population and divided the result by 40 to determine costs per person and year. We then averaged the data for every subarea and included the results in Table 1. They confirm the distribution of bedload damage costs at regional level with values of more than 215 CHF cap^{-1} yr^{-1} for the Central Alps, Valais and Ticino subareas. Reflecting the quite low financial losses and moderate percentage of affected communities, costs per person and year amount to a comparatively low 26 CHF cap^{-1} yr^{-1} in the Grisons subarea. For the Swiss Plateau and Jura, losses per person and year are even much lower (< 1.5 CHF cap^{-1} yr^{-1}).

The resulting fractions of damage costs caused by bedload transport to total damage costs are highly variable between the different subareas (Fig. 4). While in the mountainous part of Switzerland values amount to 0.3 or higher for all subareas, the Swiss Plateau and the Jura show very low fractions of less than 0.1, as most of the total financial losses are caused by inundations along larger rivers and lakes. The fraction is by far highest for the distinctly Alpine Valais subarea (ca. 0.6), followed by the Central Alps and Ticino (slightly below 0.5). At about 0.3, the Prealps subarea shows a slightly below average value compared to the Swiss mean. In summary, the subareas with an elevated fraction of bedload damage costs for the 40 yr study period generally feature a considerable cumulative financial loss induced by bedload processes. The only exception to this norm is the Grison subarea that shows both quite low bedload and total damage costs resulting in an above average ratio of approximately 0.4.

3.3 Damage due to bedload processes during major natural hazard events

Hilker et al. (2009) described in detail six major flood events registered in the damage database since 1972. We decided to resume the discussion to show how completely different the damage symptoms caused during major flood events can be, depending on the affected regions and the occurring processes. Similarly, the importance of bedload transport processes during such major events varies substantially. We added a recent event to the established list, the August 2007 flood event, because it stands in contrast to several of the other events. Table 3 includes a total of seven flood episodes and lists the total amount of financial loss for each event, the percentage of the estimated financial loss caused by bedload transport and the associated process uncertainty index.

The fraction of bedload transport damage for the individual events varies between approximately 0.04–0.06 (May 1999) and 0.86–0.92 (September 1993). These two extremes are exemplarily discussed below, together with the August 2007 event which yields a low fraction just somewhat above the fraction of the May 1999 event. Three major events (August 1987, October 2000 and August 2005) show fractions of bedload transport damage that roughly correspond to the value for the full investigation period (0.32–0.37). The event that occurred in August 1978 shows a very high percentage of bedload transport damage mainly due to floods in several rivers of the Ticino subarea that have caused excessive erosion, sediment transport and subsequent deposition.

3.3.1 The 1993 Brig sediment disaster

In September 1993, three days of persistent and extensive rainfall over the Valais and Ticino regions caused devastating damage mainly in the Upper Valais. By the afternoon of the 24 September the discharge of the Saltina River along its alluvial fan was elevated and had reached 70 $m^3 s^{-1}$. Subsequently, considerable amounts of sediment were transported into the zone of the Saltina bridge in the town of Brig. These had been mobilized upstream as soon as the discharge had reached a threshold value of 40–50 $m^3 s^{-1}$. At supply rates of about 1–1.5 $t s^{-1}$, the bedload material began accumulating below the bridge due to the locally reduced channel gradient. With increasing depth of the deposited sediment, the transport capacity of the Saltina River further decreased and the water level rose. Gradually, water started to hit the bridge and to flow off sideways, while water discharge in the channel below the bridge decreased allowing for further deposition of material. The flow cross-section underneath the bridge was progressively filled up until it was totally clogged. Finally, large-scale flooding and overbank sedimentation in parts of the municipality of Brig-Glis occurred. It is obvious that bedload processes played a key role during this flood event, amplifying the financial losses excessively (Bezzola et al., 1994; Badoux and Rickenmann, 2008). Sadly, the event caused two fatalities. The area of the Brig train station and several streets were covered up with coarse and fine sediment up to 2 m deep. Massive damage occurred on hundreds of buildings and many basements were completely filled up with material. Furthermore, infrastructure, facilities and numerous parked cars were destroyed. After the event approximately 30 000 m^3 of sediment had to be cleared. Brig-Glis was by far the municipality that suffered worst during the 24 September 1993 flood event (Röthlisberger, 1994). Total financial loss amounted to 770 million CHF, of which 86–92 % were due to bedload transport. Thus, the event ranked fourth in terms of total damage, third in terms of bedload damage, and first as an event affecting a single community (Table 3).

3.3.2 The May 1999 and August 2007 flood events

In contrast, the large flood event that occurred in May 1999 (often subdivided in two different periods 11–15 and 20–22 May, see BWG, 2000) hardly included any damage due to fluvial bedload transport processes. Snow melt in combination with rainfall led to an increase of lake and river levels, especially in the northern, less mountainous areas of Switzerland. Damage was mostly generated through stagnant inundation on lake shores and flooding along some of the larger rivers, notably in densely settled areas such as the city of Berne (Aare River) and the city of Thun (Lake Thun). Total financial loss amounted to 640 million CHF. The subareas of the Swiss Plateau and the Prealps were severely affected. Some damage was also registered in the Central Alps (partly by landslides) and the Jura along the Rhine River. As inundations occurred mainly because of very high lake levels and along low-gradient streams downstream of such lakes, bedload transport played a minor role in the reported damage processes. When the water moved back, flooded areas were often only covered by a thin layer of silt. Similarly, in August 2007 long lasting rainfall led to floods especially in the Jura and Swiss Plateau subareas, where the capacity of the regulated system of Lake Neuchâtel, Lake Bienne, Lake Morat and the lower-lying river Aare was considerably exceeded. Analogically to the May 1999 event, bedload processes were not important during August 2007 (Bezzola and Ruf, 2009). The only notable damage caused by bedload transport was reported in the municipality of Roche (canton Vaud), where a steep torrent deposited a considerable amount of sediment in the centre of the village.

4 Discussion

4.1 Data quality

For some events comprised in the Swiss flood and landslide damage database it is difficult to comprehend the exact course of event and thus to identify whether bedload transport deposition or erosion played a crucial role in the damage process or not. We have introduced a process uncertainty index ranging from 1 to 3 to provide a qualitative evaluation of the reliability of our data regarding the significance of bedload transport during an event. The mean process uncertainty index calculated for the bedload damage cost estimations per pentad varies between 1.27 (1992–1996) – which is a very good score – and 2.27 (1972–1976) – which has to be rated as a rather poor score –, while the 40 yr long-term average amounts to 1.78 (Fig. 5 and Table 2). Early pentads of our dataset show higher process uncertainty indices than the later pentads and overall it seems that the process uncertainty is decreasing with time. As a matter of fact, data acquisition and recording has improved in the Swiss flood and landslide damage database during the last 40 yr. First, the quality of the raw data (mainly newspaper articles) has increased notably. Due to an increasing public awareness of natural hazards, the completeness and accuracy of media coverage has improved over time, also for events that occur in remote parts of the country. However, regional variations in the quality of event reporting still persist (Hilker et al., 2009). Second, the workflow related to data acquisition and recording within the database has been considerably optimized over the last 15 to 20 yr. Today the whole process is handled digitally.

Furthermore, high process uncertainty indices were reported for the 1978 and 1987 major events (Table 3). During major events, a very large quantity of information is available which in the pre-digital era made it difficult to properly process all the data within the damage database. Here again, the September 1993 event represents an exception. Bedload transport processes played a key role back then and undoubtedly caused most of the financial losses recorded which is reflected in a very low process uncertainty index (Table 3).

When averaged over months, the index appears to be lower during summer and autumn, when virtually the totality of financial losses due to bedload processes occur, than in winter and spring (with the exception of November, see Table 2). From November to March, the process uncertainty index actually shows poor to very poor results. We assume that this is because during these months, the smaller and less significant flood events are not often described accurately. Consequently, it is generally difficult to assess if bedload transport processes were really involved in the damage process or not.

Finally, we subdivided all database entries featuring bedload transport damage into four classes according to their process uncertainty index (Table 4). The width of a class amounts to 0.5 index points. Subsequently, bedload damage costs of all entries within a certain class were added up. It appears that nearly half of all damage costs that we attributed to bedload damage processes over the entire study period falls into the lowest class (indices < 1.5), and thus shows a very low to low process uncertainty. About as much financial loss (47 %) is ascribed to the two highest classes and is associated with medium to very high process uncertainty. In summary, more than 50 % of our estimates show good credibility.

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We have shown above that process uncertainty is decreasing within our study period (Fig. 5). This is confirmed by decadal data of bedload damage costs subdivided into uncertainty index classes (Table 4, columns 5 to 8). The percentage of financial losses associated to very low to medium process uncertainty (classes 1 and 2, indices < 2) is low in the first decade (21.5 %) but increases strongly thereafter to reach 46.4 % in the second decade. In the third and fourth decade the values lie above 60 % (82.4 and 60.2 % respectively) and suggest considerable improvements in the evaluation of damage data.

4.2 Possible controls on bedload damage costs

To investigate potential controls on damage costs caused by fluvial bedload deposition and erosion, we plotted our estimates against several different parameters (Fig. 6). We also plotted the fraction of bedload damage costs to total damage costs (Fig. 7) as well as costs per capita (Fig. 8) against the same parameters. The damage data used in all graphs of Figs. 6 through 8 represents cumulative sums per subarea.

4.2.1 Stream-channel gradient

The first parameter applied to test the estimates of bedload transport damage is the channel gradient of streams that drain hydrological catchments within the subareas. Bedload transport damage costs display increasing values with increasing means (Fig. 6a) and standard deviations (Fig. 6b) of channel gradient. The correlation is stronger for the standard deviation ($R^2 = 0.65$) suggesting that considerable gradient changes are more favourable to bedload damage occurrence than simply steep gradients. Correlations increase when channel gradient is plotted against the fraction of bedload damage to total damage (Fig. 7a and b). This indicates that compared to the totality of damage induced by other natural hazard processes considered in the database, bedload transport damage has a stronger positive correlation with channel gradient, as would be expected from process considerations. For example, costly large scale inundation is likely to be most important in flat lowland areas (e.g. along lake shores or large rivers in wide valley bottoms). Also, bedload damage shows a stronger link to channel gradient mean and standard deviation when normalized with population (Fig. 8a and b). Large agglomerations are generally situated in plains and population density tends to diminish in increasingly steep and precipitous terrain, explaining this observation.

The strength of channel gradient as a predictor for regional bedload damage costs is not surprising. Many of the simple prediction equations give bedload transport capacity as a function of channel slope and discharge (e.g. Rickenmann, 1991, 2001; Bathurst et al., 1987).

4.2.2 Elevation

When plotted against bedload damage costs, mean elevation (Fig. 6c) and standard deviation of elevation (Fig. 6d) yield similar results as stream gradient data, but with weaker correlations coefficients. Again, the standard deviation appears to be a better predictor of damage costs than the mean value. A high standard deviation of elevation suggests rough and rugged terrain with considerable slope variation, whereas high mean elevation could possibly also be observed on e.g. a high plateau. Normalization of bedload damage with total damage (Fig. 7c and d) and with population (Fig. 8c and d) enhances the predictive quality of elevation data. Especially, the correlation of the normalized damage data with the standard deviation of elevation is very high with coefficients of 0.91 (fraction of bedload damage to total damage) and 0.85 (bedload damage per person).

The correlation coefficients achieved by plotting the fraction of bedload damage with both gradient and elevation data (Fig. 7a–d) score in the range between 0.78 and 0.91; higher than the coefficients obtained by simply plotting bedload damage costs with gradient and elevation data (R^2 of 0.26–0.65, Fig. 6a–d). The reason for this partly lies in the respective position of the Grisons data point (7). With rather low bedload damage costs for a mountainous subarea (Fig. 4), it plots well below the regression line in Fig. 6a–d. But because the total damage costs recorded for the Grisons subarea are comparatively low as well (Fig. 4), the resulting ratio of bedload damage to total damage plots in the very vicinity of the regression line in Fig. 7a–d. It is not fully understood why the Grisons subarea yields such low overall losses and bedload transport losses compared to other Alpine subareas. However, we assume that a combination of methodological shortcomings (a lower media echo regarding natural hazards leading to lower publication coverage as well as a comparatively short study duration) and possible differences in geomorphic channel capacity may be relevant.

4.2.3 Precipitation

Bedload damage costs and mean annual (subarea) precipitation have a fairly strong positive correlation (Fig. 6e) with R^2 of 0.51. In general, higher precipitation leads to larger discharge values in streams and torrents. With available material in the catchments, high flows, in turn, can mobilize bedload and under disadvantageous conditions overbank sedimentation or bed erosion occur, eventually causing damage costs. In contrast, the fraction of bedload transport damage to total damage is quite weakly correlated with subarea precipitation (Fig. 7e). It seems that the fraction increases with annual precipitation, but the high ratios observed for the Grisons and Valais subareas, associated to relatively low precipitation values (data points 5 and 7 in Fig. 7e), attenuate the relationship. When damage costs are normalized with subarea population (Fig. 8e) the positive correlation with precipitation is also very weak. Rainfall turns out to be a poor predictor for both the ratio of bedload damage costs and financial losses per person.

4.2.4 Population density

Bedload damage costs and (subarea) population density are negatively linked with each other, meaning that densely populated subareas tend to encounter less financial losses (Fig. 6f). The underlying correlation is not very strong though, mainly because of

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the moderate bedload damage costs in the most scarcely populated Grisons subarea (data point 7 in Fig. 6f). Because total damage costs reported in the Grisons are low too (above and Fig. 4), its ratio of bedload damage to total damage lies within the range of ratios observed in other mountainous subareas. As a consequence, the correlation displayed in Fig. 7f is considerably stronger (R^2 of 0.70) than the correlation of the non-normalized damage data with population density (R^2 of 0.33, Fig. 6f). Finally, when plotting bedload damage costs per person against population density a fair correlation is achieved with a coefficient of 0.54 (Fig. 8f).

Our study suggests (at the regional level) that bedload damage costs decrease with increasing population density which might seem contradictory because densely populated areas generally imply a concentration of goods and hence a higher damage potential. But in reality, very intense bedload transport processes eventually leading to considerable financial losses only occur in zones close to steep streams and torrents where population density is often widely restricted.

4.2.5 Verification of controls using data at the municipal level

To verify if our findings at the regional level (Figs. 6–8) also apply to the municipal level, we plotted normalized damage costs caused by bedload transport processes in Swiss communities against spatial mean values of channel slope, elevation, precipitation, and population density (Fig. 9a, c, e, and f, respectively) and against standard deviation values of channel slope and elevation (Fig. 9b and d, respectively). None of the correlations observed at the regional level apply at the municipal level (all $R^2 < 0.16$). Data points in all graphs show a very large scatter which does not allow any speculation on potential connections. This fact, however, is not very surprising, because (i) only a few municipalities have been seriously affected by a major meteorological event during the 40 yr study period (Fig. 3), whereas the majority of municipalities only show very small damage costs per person and square kilometre; (ii) furthermore, many communities do not feature any torrent or mountain stream with a high damage

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potential due to bedload transport processes, even though they might be mountainous and show a high mean elevation or/and mean channel slope.

For all graphs of Fig. 9, municipal bedload damage costs per area and person were classified into logarithmically distributed bins in x axis data. Binned means of normalized costs were then added to the graphs (black circles). On average, we find positive correlations of damage costs per capita per unit area with the mean and standard deviation of the channel bed slope, with mean and standard deviation of elevation and with precipitation. We find a negative correlation with population density. The observed correlations are as expected and can be explained by similar reasonings as are put forward above.

4.3 Importance for fluvial bedload transport prediction

As shown above, on average, fluvial bedload transport processes cause substantial damage costs in Switzerland. Some flood events occurred in the last few decades were dominated by bedload erosion and deposition and can be rated as proper sediment disasters. We demonstrate that especially steep mountainous areas and areas characterized by abrupt changes in channel gradient are endangered by severe bedload transport processes.

Thus, the threat of large bedload transport events must not be underestimated in mountainous regions. Of course, this is no novelty for Alpine communities, but our long-term analysis of the impact of bedload transport processes for a national economy represents a rare quantitative documentation of the problem. Our results emphasize the need for methods to predict sediment transport associated with large floods. Such calculations are required and essential for hazard mapping, the design of structural measures along streams and the planning of organizational measures in municipalities. Substantial losses will only be avoided if bedload volumes are predicted with reasonable accuracy. However, approaches are needed that are easily applicable to a range of steep torrents and streams, not only in privileged parts of the world but also in regions with developing economies where highland inhabitants are more

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vulnerable to natural hazards and political-economic marginalization than populations elsewhere (Marston, 2008).

Recently, several authors have responded to this requirement and have developed interesting approaches. Nitsche et al. (2011) addressed the problem that many bedload transport equations used in practice considerably overestimate transport in streams by taking into account the contribution of macro-roughness elements to flow resistance. The method needs approximately one day of field work per representative reach to carry out (additional) field measurements (Nitsche et al., 2012), and the obtained results achieve considerable improvements in transport prediction. Recking (2010) proposed a formula that was established using an extensive data set of flume and natural river data but is based on only limited knowledge of bed surface material. The method has the advantage of not being data nor time consuming, yields satisfactory results, especially at low transport conditions, and thus provides a rapid and reliable estimate of the bulk transport rate.

Albeit being too expensive and time consuming to be broadly applied in mountainous catchments, accurate bedload transport measurements are nonetheless of crucial importance to calibrate predictive equations (Rickenmann et al., 2012). Currently, cheap alternative monitoring technologies based on acoustics, vibrations, or impact measurements are being developed (Gray et al., 2010), but still need direct measurements using traps or retention basins for calibration.

The degree of safety to be achieved through protection measures (the protection objective) is widely defined by the damage potential in a given area. We assume that in Switzerland, there is no substantial difference between the protection objectives along steep mountain streams prone to bedload transport and protection objectives in areas adjacent to large streams and lakes more prone to large-scale, rather static inundations. Hence, the ratio of bedload damage costs to total costs of 0.32–0.37 seems a representative value for Switzerland which is not likely to considerably increase or decrease in the near future. In comparison to other mountainous regions of the world, technical and organizational protection measures along torrents and

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steep streams are quite well developed in Switzerland. Thus, we suspect that in other countries, especially less privileged and developed ones, the importance of bedload transport processes for overall natural hazard damage costs might be somewhat larger.

5 Conclusions

In this study, we assessed the contribution of fluvial bedload transport erosion and deposition to total financial damage caused by natural hazards. For this purpose, we re-evaluated data of the Swiss flood and landslide database, which collects information on direct financial damage of naturally triggered floods, debris flows and landslides and covers the period from 1972 to 2011. Thousands of database entries were individually examined and it was assessed whether bedload transport erosion or deposition contributed to the occurred damage or not. In cases where it did, upper and lower limits of financial losses caused by or related to transport processes were estimated, and process uncertainty was considered.

In the 40 yr study period, fluvial bedload transport processes have induced cumulative financial damage costs in Switzerland that lie between 4.3 and 5.1 billion CHF (lower and upper limits of our estimations). These losses, however, are highly variable both temporally and spatially. While in 2005, damage costs amounted to more than 1140 million CHF, 15 individual years have damage costs of less than 10 million CHF (mean of the lower and upper estimates). With mean annual financial losses of approximately 118 million CHF, the median is only about 15 million CHF. The seasonal distribution is highly variable because summer (June–August) is responsible for about 75 % of the costs (~ 56 % in August alone) and autumn (September–November) for about 23 %. The spatial distribution of bedload damage costs reveals that municipalities with medium or high cumulative losses are concentrated in the mountainous part of Switzerland. While 15 communities show financial losses of 50 million CHF or more, a large number of communities all over Switzerland have not been exposed to any serious damage related to bedload transport, most of which are located in the lowlands.

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This pattern is confirmed when the cumulative bedload transport damage costs are aggregated for seven Swiss subareas: only about 5 % of the costs occurred in the two non-Alpine subareas (Jura and Swiss Plateau), about 15 % in the Prealps subarea and the principal part of the costs were generated in the four highly mountainous subareas (Central Alps, Valais, Ticino, and Grisons).

When put into relation to the overall damage costs caused by various natural hazard processes according to the flood and landslide database, we obtain a ratio of 0.32–0.37 for the nationwide 40 yr bedload damage dataset. This fraction too, is variable in space and time. For single years, a low value of approximately 0.02 was determined for 1988 and a high value of 0.72 for 1978, while the median value of all 40 yr amounts to 0.18 (mean of lower and upper estimates). The resulting fractions for the different subareas show a distinct pattern. Very low values of less than 0.1 are reported for the Jura and Swiss Plateau subareas. In contrast, the Prealps have a much higher ratio of approximately 0.3 and in the Alpine subareas more than 40 % of all damage costs are caused by bedload transport processes.

Potential controls on bedload damage costs, damage costs per person and the fraction of bedload costs to total costs were tested at the regional level. The strongest correlations resulted between (i) the fraction of bedload losses and mean value/standard deviation of channel gradient and elevation ($R^2 > 0.78$), and (ii) the damage costs per person and the standard deviation of channel gradient and elevation (R^2 of 0.75 and 0.85, respectively). The absolute damage costs caused by bedload transport processes turned out to be more difficult to predict applying subarea characteristics, resulting in somewhat weaker correlations. Furthermore, mean precipitation and population density are poor to moderate predictors for damage costs, costs per person and ratio of losses by bedload processes.

After more than a century of research, bedload transport processes are still not sufficiently understood. Our analysis quantitatively demonstrates the role of bedload transport as an important natural hazard and a considerable financial source of risk in Alpine environments. Thus, the study confirms the need for future structured research

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programmes on fluvial bedload transport in steep streams. Specifically, methods to predict sediment transport associated with large floods and capable of producing reasonably accurate information vital for flood mitigation measures and for the design of protective infrastructure are required.

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Table 1. Characteristics of the seven Swiss subareas applied in this contribution (cf. Fig. 1).

No.	Subarea name	Subarea size	Subarea population[a]	Mean elevation	Mean annual precipitation[b]	Number of municipalities[c]			Bedload damage per person and year[d]
		[km^2]	[1000]	[m a.s.l.]	[mm]	total	affected	[%]	[CHF cap^{-1} yr^{-1}]
1	Jura	4207	1018.6	804	1307	417	109	0.26	0.83
2	Swiss Plateau	11 016	4938.2	560	1151	1271	420	0.33	1.26
3	Prealps	4673	840.3	1007	1587	237	170	0.72	19.3
4	Central Alps	6669	364.1	1639	1689	132	119	0.90	229.3
5	Valais	4798	264.4	2199	1308	124	109	0.88	215.1
6	Ticino	3252	344.9	1424	1803	174	100	0.57	222.6
7	Grisons	6619	184.2	2044	1192	160	87	0.54	25.9

[a] According to the Swiss Federal Statistical Office for the year 2011.
[b] Data source: MeteoSwiss (1961–2011).
[c] As of end of 2011; the number of affected municipalities denotes municipalities with at least one entry reporting bedload transport damage.
[d] This value represents the mean of all municipalities (affected or not) for a given subarea.

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Table 2. Monthly distribution of bedload erosion and deposition damage estimates (cumulative data for the period 1972–2011).

Month	Bedload damage (lower est.)		Bedload damage (upper est.)		Total costs of damage[a]	Fraction bedload damage/tot. damage[b]	Process uncertainty index[c]
	[million CHF]	[%]	[million CHF]	[%]	[million CHF]	[–]	[–]
Jan	0.8	< 0.1	1.1	< 0.1	49.3	0.02	2.15
Feb	17.7	0.4	26.4	0.5	239	0.09	2.55
Mar	2.0	< 0.1	3.4	< 0.1	51.5	0.05	2.22
Apr	3.5	< 0.1	4.9	0.1	84.8	0.05	1.90
May	46.2	1.1	65.4	1.3	1018	0.05	2.00
Jun	127	2.9	161	3.2	1173	0.12	1.52
Jul	707	16.3	860	17.0	1991	0.39	1.87
Aug	2415	55.6	2826	55.8	6609	0.40	1.91
Sep	699	16.1	750	14.8	1180	0.61	1.27
Oct	306	7.1	341	6.7	861	0.38	1.60
Nov	16.5	0.4	23.5	0.5	234	0.09	2.32
Dec	1.3	< 0.1	2.4	< 0.1	64.3	0.03	2.60
All year	4342	100	5065	100	13 555	0.35	1.78

[a] According to the Swiss flood and landslide damage database.
[b] For the calculation of the fraction of bedload damage costs to total damage costs, the mean value of the two estimates was applied.
[c] The process uncertainty index given here applies for all bedload damage estimations within the given month (index assessed using the upper damage estimates for weighting single database entries).

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Table 3. The impact of bedload transport processes for damage costs during seven major flood events in Switzerland (since 1972).

Year	Date	Most affected subareas[a] (Table 1)	Total costs of damage (rounded)	Fraction bedload damage/tot. damage (lower est.)	Fraction bedload damage/tot. damage (upper est.)	Process uncertainty index[b]
			[million CHF]	[–]	[–]	[–]
1978	7–8 Aug	6 (95 %)	1020	0.68	0.80	2.01
1987	24–25 Aug	4 (69 %), 6 (16 %), 5 (15 %)	1140	0.34	0.42	2.23
1993	24 Sep	5 (> 99 %)	770	0.86	0.92	1.23
1999	11–15/ 20–22 May	2 (49 %), 3 (28 %), 4 (11 %)	640	0.04	0.06	2.08
2000	14–15 Oct	5 (68 %), 6 (25 %)	730	0.34	0.38	1.63
2005	21–22 Aug	4 (35 %), 3 (27 %), 2 (21 %)	3120	0.34	0.39	1.80
2007	8–9 Aug	2 (44 %), 1(39 %), 4 (13 %)	390	0.14	0.17	1.56

[a] Subarea numbers according to Table 1 and Figs. 1 and 3; percentage relate to total financial loss in a given subarea.
[b] The process uncertainty index given here applies for all bedload damage estimations within the given flood event (index assessed using the upper damage estimates for weighting single database entries).

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Table 4. Bedload damage costs associated to a certain range of the process uncertainty index.

Class of process uncertainty index	Range	Bedload damage costs, full period (upper est.)		Bedload damage costs (72–81)	Bedload damage costs (82–91)	Bedload damage costs (92–01)	Bedload damage costs (02–11)
		[million CHF]	[%]	[%]	[%]	[%]	[%]
1	1.00–1.49	2366	46.7	18.2	41.8	78.4	48.4
2	1.50–1.99	317	6.3	3.3	4.7	4.1	11.8
3	2.00–2.49	1113	22.0	56.6	19.3	2.7	9.8
4	2.50–3.00	1269	25.0	21.9	34.3	14.8	29.9
Total	1.00–3.00	5065	100	100	100	100	100

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Fig. 1. Location of the seven subareas for which bedload damage data was aggregated according to Table 1 (1 – Jura, 2 – Swiss Plateau, 3 – Prealps, 4 – Central Alps, 5 – Valais, 6 – Ticino, 7 – Grisons) displayed together with the digital elevation model of Switzerland (data: BFS GEOSTAT/Federal Office of Topography swisstopo).

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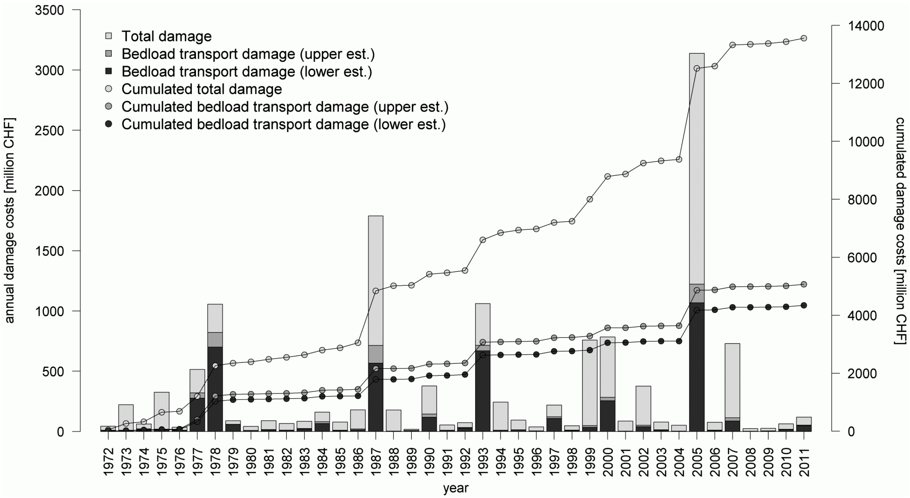

Fig. 2. Annual cost of damage caused by bedload transport processes in Switzerland from 1972 to 2011. While total bar length indicates the overall damage costs as recorded in the Swiss flood and landslide database (Hilker et al., 2009), the two darker grey tones give the lower and upper estimates for bedload transport damage cost. The different lines show cumulative costs for overall damage and damage due to bedload transport processes.

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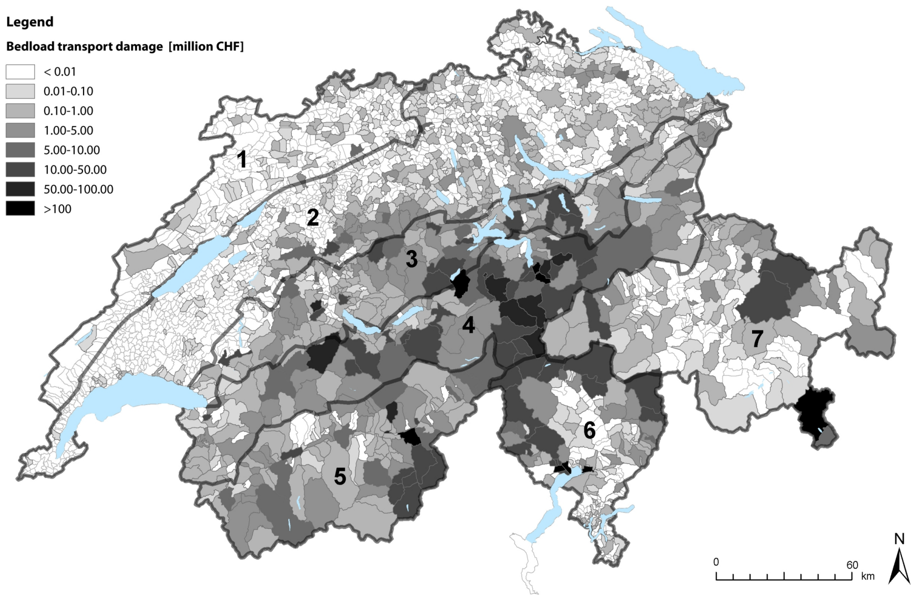

Fig. 3. Spatial distribution of damage costs caused by bedload processes over the entire 40 yr study period at the municipal level (mean of the lower and upper estimates were applied). The bold black lines indicate the borders of the subareas (Fig. 1; Table 1). Note that 460–535 million CHF of losses could not distinctively be assigned to a single municipality.

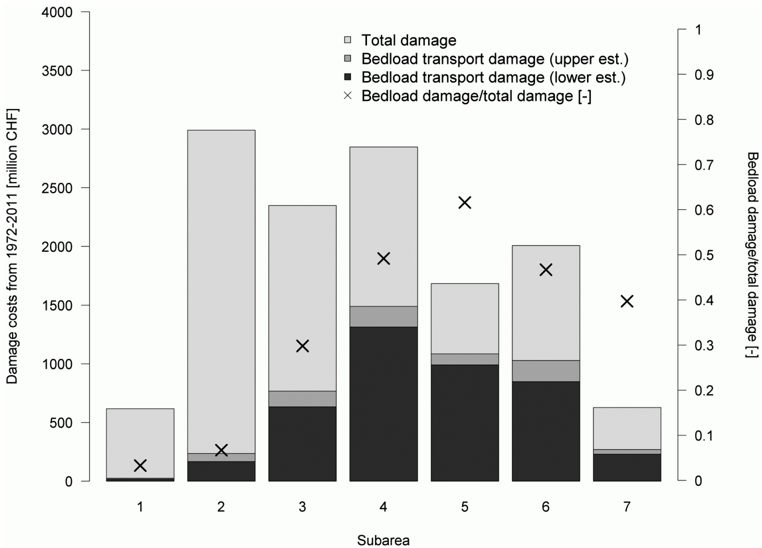

Fig. 4. Total damage costs and estimated damage costs by bedload transport for the seven subareas (Fig. 1; Table 1). Crosses indicate the ratio of costs caused by bedload transport processes to total costs (mean of the lower and upper estimates were applied to calculate ratios). Note that 145–165 million CHF of losses could not distinctively be assigned to a subarea.

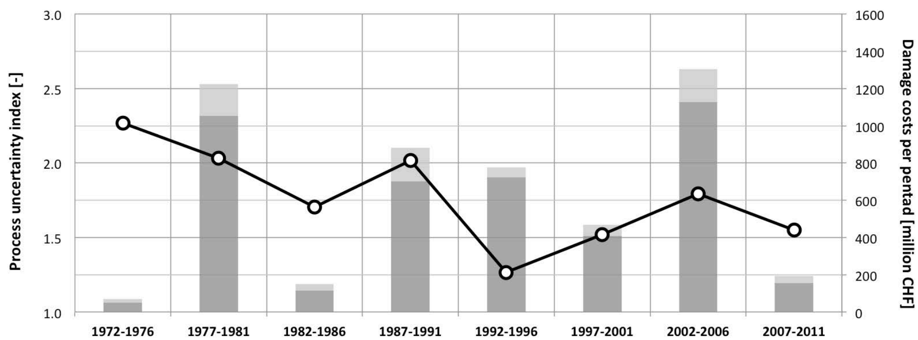

Fig. 5. Process uncertainty index for all bedload damage cost estimations per pentad (index describes data quality and was assessed using the upper damage estimates for weighting single database entries). The grey bars in the background indicate the accumulated bedload damage costs per pentad (lower and upper estimates).

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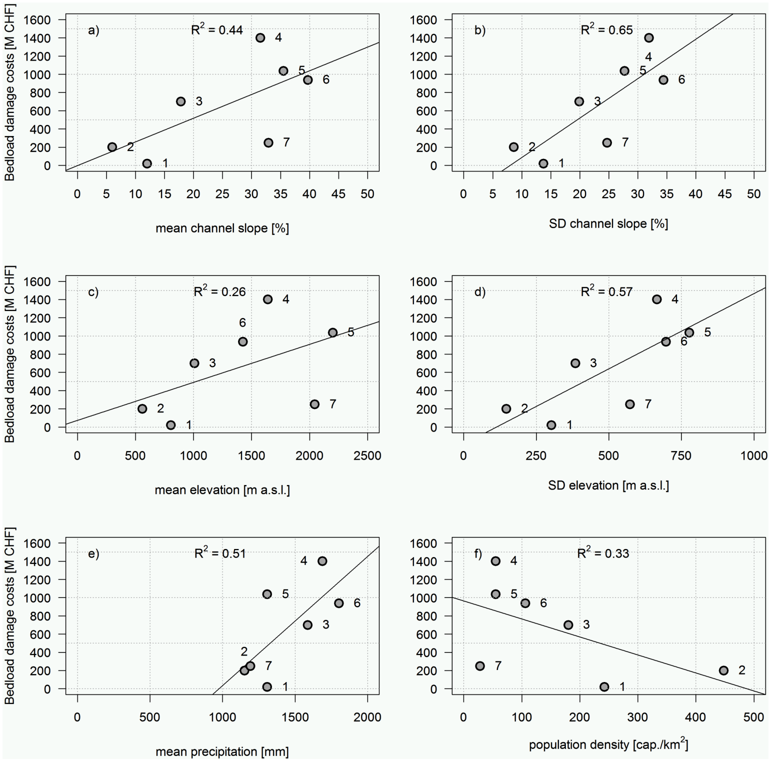

Fig. 6. Relation, for the seven different subareas, between the cumulative bedload damage costs and **(a)** the mean/**(b)** standard deviation of channel slope, **(c)** the mean/**(d)** standard deviation of elevation, **(e)** the mean of annual precipitation, **(f)** the population density. Note that the average of the lower and upper bedload damage cost estimates was applied. Numbers next to the data points denote subareas according to Table 1 and Fig. 1.

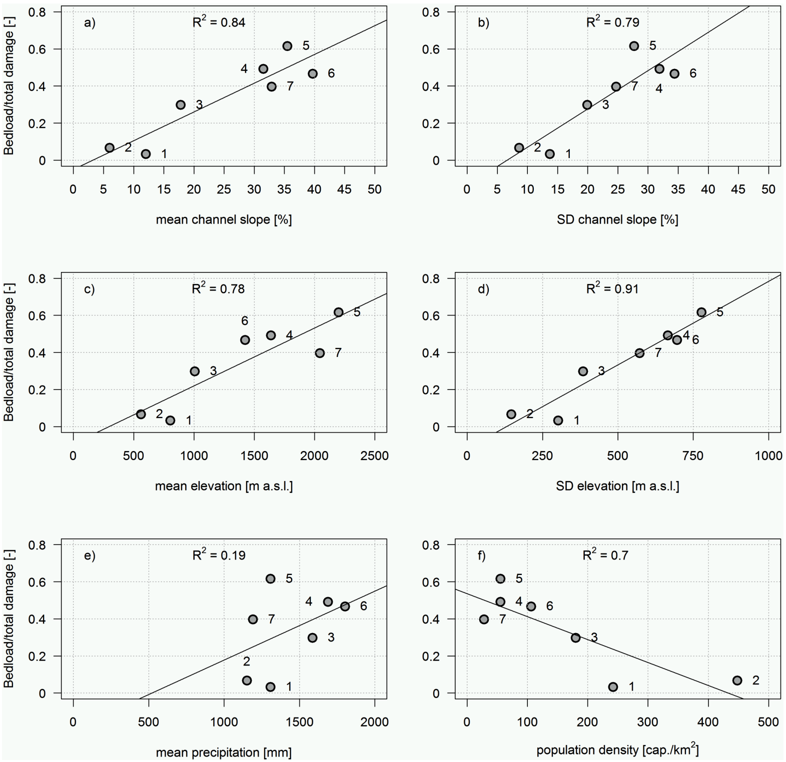

Fig. 7. Relation, for the seven different subareas, between the fraction of bedload damage costs to total costs and **(a)** the mean/**(b)** standard deviation of channel slope, **(c)** the mean/**(d)** standard deviation of elevation, **(e)** the mean of annual precipitation, **(f)** the population density. Note that the average of the lower and upper estimates was applied to determine the fractions. Numbers next to the data points denote subareas according to Table 1 and Fig. 1.

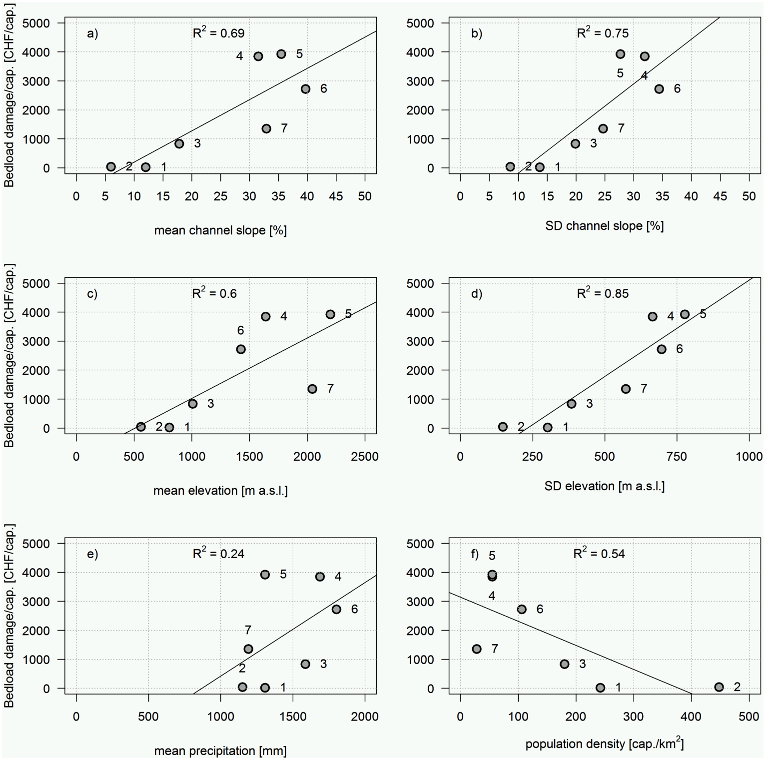

Fig. 8. Relation, for the seven different subareas, between the cumulative bedload damage costs per capita and **(a)** the mean/**(b)** standard deviation of channel slope, **(c)** the mean/**(d)** standard deviation of elevation, **(e)** the mean of annual precipitation, **(f)** the population density. Note that the average of the lower and upper estimates was applied to determine the damage costs per capita. Numbers next to the data points denote subareas according to Table 1 and Fig. 1.

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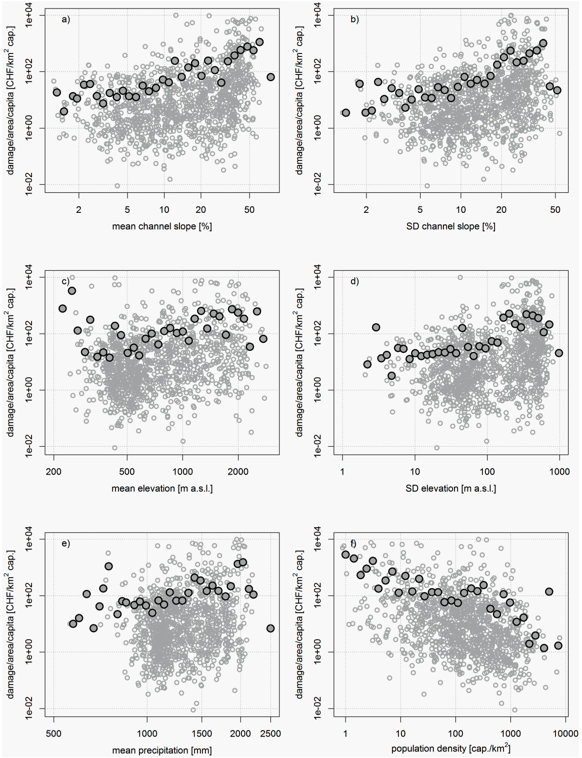

Fig. 9. Relation between municipal bedload damage costs normalized by area and population and **(a)** the mean/**(b)** standard deviation of channel slope, **(c)** the mean/**(d)** standard deviation of elevation, **(e)** the mean of annual precipitation, and **(f)** the population density. Grey circles represent the individual municipalities affected by bedload transport damage between 1972 and 2011. The black circles represent binned means.

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Damage costs due to bedload transport processes in Switzerland

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