

A Sediment Budget of the Upper Kaunertal

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Abstract

This chapter presents the sediment budget of the Upper Kaunertal (Kauner valley, Ötztal

Alps, Austria) for the years 2012–2014 as obtained in the framework of the PROSA (high-resolution measurements of morphodynamics in rapidly changing PROglacial Systems of the Alps) research project. An important methodological basis of this high-mountain sediment budget is the usage of study area-wide LiDAR data (TLS and ALS) of comparatively high temporal and spatial resolution to measure rates of erosion and deposition, and to regionalize/upscale rates at the local scale. After several billion measurement points and data from fieldwork, mapping, and modeling efforts had been processed and evaluated, it was possible to identify and quantify sediment transfer by all relevant processes at the scale of the 62 km² study area. These processes include rockfall of three different magnitude classes, debris flows, avalanches, creep on talus, fluvial processes (hillslopes and main fluvial system), rock glaciers, and glaciers. After a short presentation of the process-specific methods to obtain catchment-wide rates, we discuss process-specific results and the budget. The sediment budget does not only show the relative importance of the mentioned processes and spatial subunits (proglacial vs. non-proglacial) in the Upper Kaunertal. It also gives insight into the importance of high-magnitude events and the configuration of the sediment transport system.

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PROSA project • Sediment budget •
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17.1 Introduction

Most (pro)glacial sediment budgets established so far have mainly focused on suspended and bedload transport in the main channel(s) of proglacial areas (Chap. 15). Hillslope processes, such as slope-aquatic processes or mass movements (i.e., debris flows, slides, and rockfalls), have received comparatively little attention, causing research need in complete high-mountain sediment budgets, especially under global warming conditions. As high-mountain areas have been comparatively weakly impacted by human action, these areas can be used to establish baselines for the investigation and modeling of geomorphic processes under future climate conditions. This is why the construction of a present-day sediment budget of the Upper Kaunertal is seen as a valuable contribution to both sediment budget and high-mountain geomorphology research. The main objectives in construction of the sediment budget of the Upper Kaunertal are (i) to assess the relative importance of different geomorphic processes in the study area and (ii) to obtain an estimate of the proportion of mobilized sediment that finally reaches the outlet of the catchment, thereby enabling inferences on the state of connectivity in the Upper Kaunertal.¹

The catchment (c. 62 km²) under study is located in the Ötztal Alps, a mountain range in the Central Alps of Austria (see Chap. 1). Crystalline rocks make up the rockwalls and form peaks up to 3583 m high. The defined catchment

outlet is constituted by the mouth of the main river (“Fagge”) into the Gepatsch reservoir at 1810 m. A large share of the catchment is covered by glacier ice (c. 31% as of 2012). At Weißsee weather station (2500 m), the average annual precipitation is 983 mm and the average air temperature is −0.6 °C. Coniferous forest can be found below c. 2150 m. A map of the study area showing some place names used in this chapter is shown in Fig. 17.1.

Processes identified as being of relevance for the Upper Kaunertal sediment budget (based on field observations made during the first field visits and insights gained during the preparation of the geomorphological–geological map) are

- Mass wasting processes, including rockfall of all magnitudes (Sects. 17.4.1 and 17.4.2; see also Chap. 9; Vehling 2016; Vehling et al. 2016, 2017; Heckmann et al. 2016) and rock slides (Sect. 17.4.4; Chap. 9)
- debris flows (Sect. 17.4.3; see also Chap. 11; Haas et al. 2012)
- full-depth avalanches (Sect. 17.4.5)
- hillslope processes such as slope wash and linear erosion (Sect. 17.4.7; see also Chap. 11)
- periglacial creep (rock glaciers; Sect. 17.4.6; Chap. 7; Berger et al. 2004; Hausmann et al. 2007; Krainer et al. 2007; Dusik et al. 2015)
- glacial processes (Chap. 5; Giese 1963)
- fluvial processes in the main channels (Chap. 13; Baewert and Morche 2014).

The dissimilarity in mechanics and controlling factors of these processes requires a wide range of measurement, data processing, mapping, and modeling techniques to arrive at sediment transfer rates valid for the whole catchment. As the focus of this contribution is on results rather than measurement, the discussion of methodological aspects was kept to a minimum. Interested readers are referred to the Ph.D. thesis of the first author (Hilger 2017) and the publications mentioned above. The final sediment budget of the Upper Kaunertal as a meso-scale catchment spanning multiple altitudinal zones is the result of a collaboration of all sub-projects of the PROSA project (see Chap. 1).

¹This chapter contains results also discussed in the dissertation of the main author (Hilger 2017). While almost no content was directly copied unchanged, it is likely that the way of argumentation and some phrases can also be found in the dissertation.

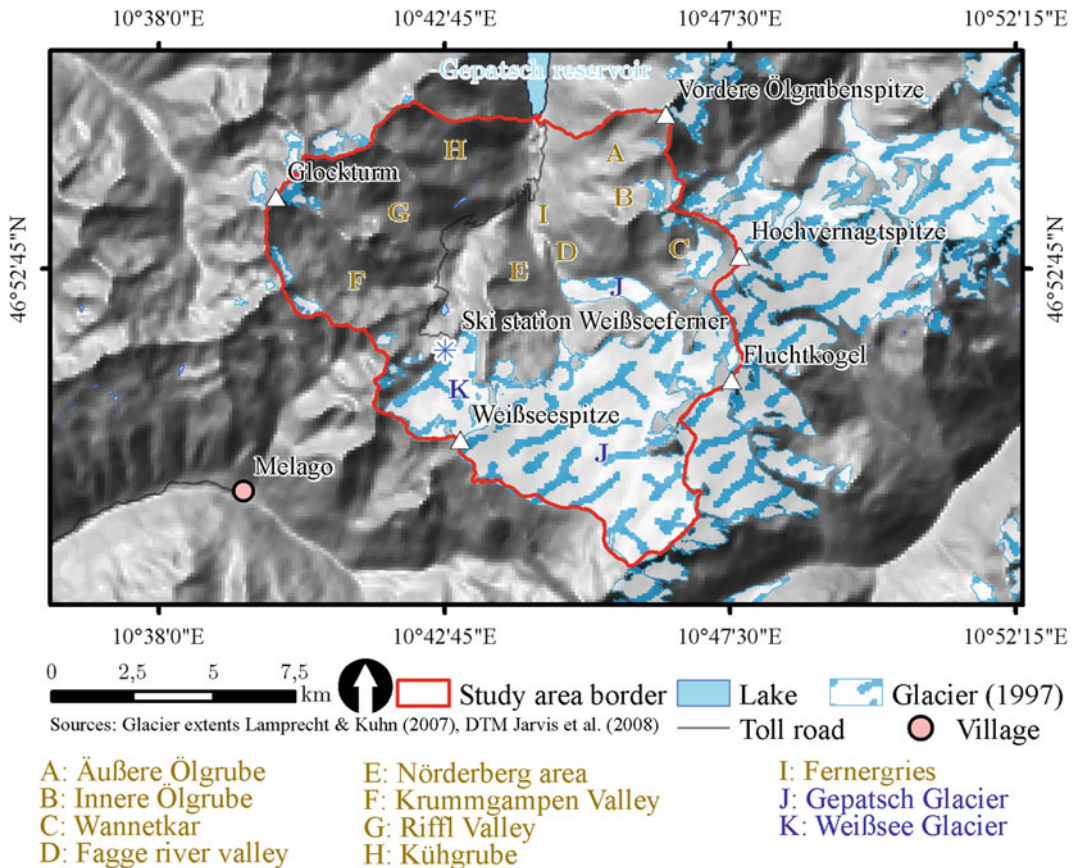


Fig. 17.1 Place names within the PROSA project study area used in this chapter. Figure taken from Hilger (2017)

17.2 Data and Methods

The data used for the construction of the sediment budget were acquired, processed, and evaluated by five different working groups over the span of about three years; in general, the data can be assigned to one of four distinct categories:

- Measurements using “classical” techniques, such as discharge measurements (Chap. 13), rockfall collectors (Chap. 9), hill slope transport measurements with troughs, extensometer measurements in deep-seated gravitational slope deformations (Chap. 9) or geophysical investigations (Chaps. 5 and 7)
- measurements on the hillslope or plot scale using airborne and terrestrial LiDAR (e.g., Chaps. 9 and 11)

- historical aerial imagery, and
- mapping results produced from the former two.

A unifying characteristic of almost all work on the construction of the sediment budget and methodological backbone of PROSA project is the high relevance of light detection and ranging (LiDAR) data. Several billion LiDAR measurement points with a precision of less than 10 cm using both terrestrial (more than 1.5 bn points) and airborne laser scanning (ALS, more than 4.5 bn points) have been acquired, processed, and evaluated for the construction of the sediment budget.

TLS data have been acquired using two different Riegl TLS devices one to four times a year at different monitoring stations. The survey frequency depended on the elevation and accessibility of the monitoring station. In total, 40

monitoring stations spanning a wide range of elevations, aspects, lithologies, and dominant process areas have been maintained, yielding over 200 TLS topographic surveys that were used for the investigation of surface changes and related sediment transfer by different processes (Fig. 17.2). Airborne laser scanning data used for the results presented in this chapter were acquired by Milan Geoservice GmbH in July 2012, October 2012, and July 2014.

After having undergone an elaborate point cloud classification work flow, all LiDAR measurement points were used to construct digital terrain models (DTMs). The relatively high point density of the LiDAR data allowed spatial raster resolutions higher than one meter. Multitemporal digital elevation models (DEMs) were used to compute DEMs of difference (DoD) to interpret the spatial distribution of negative (erosion) and positive (deposition) changes in surface elevation and to compute volumetric sediment budgets (“morphological budgeting”). DEM uncertainty was propagated into DoDs and volumetric budgets using standard Gaussian error propagation and significance tests (Lane et al. 2003; Glira et al. 2014). The resulting surface change patterns allowed for interpretation and process identification. DTMs were also used for the derivation of a wide range of land surface parameters (e.g., slope, roughness). These, in turn, served as input for spatial numerical models used for regionalization and (geomorphological) mapping.

Historical aerial photographs and orthophotos were acquired from the Austrian federal office of geodesy (BEV, Vienna) and Milan Geoservice GmbH for a total of 14 different dates ranging from June 1953 to July 2014. While some of these volumes were orthophotos, imagery from other dates was orthorectified using Trimble’s Inpho software package. The followed work flow corresponds to the classical work flow of digital stereo photogrammetry (cf. Schulz and Dornblut 2002 for more information). The procedure resulted in a global accuracy of between 0.4 and 0.5 pixels (between 10 and 25 cm) for the

different image blocks. Depending on the scale and resolution of the input images, the ground resolution of the resulting orthophotos was fixed between 20 and 55 cm.

17.3 A Geomorphological Map of the Upper Kaunertal

Given historical imagery of 14 different dates and multiple ALS survey results and their derivatives, it was possible to produce detailed maps of vegetation classes, sediment storages, and geomorphic activity for the whole catchment. The sediment storage map, as one of the most important foundations for an identification or process links, was prepared at a scale of c. 1:6000. In addition to the mentioned DTM and orthophotos, field observations and data from the literature (e.g., data on historical glacial extents, as in Kerschner 1979) were taken into account. From the beginning, the map was conceptualized to serve the aim of model-based process-link analysis. As using standard point- and line-based symbology set forth, e.g., by Kneisel et al. (1998), does not lend itself to GIS-based analysis (such as calculating areal proportion of landform types, analysis of landform topology), the map was constructed in two versions. Non-overlapping polygon objects representing sediment storages and process areas serve as the basis for GIS analysis, while the more traditional version (with storage landforms represented by point symbols) can serve as guidance in the field and the purpose of visualization. The map was generated with contributions from different sub-projects of the PROSA project (see Chap. 1). About 6000 units were mapped by hand and morphologically undifferentiated bedrock class polygons were further subdivided into aspect-based rockwall sections using a moving-window-based approach. The final geomorphological map analyzes the study area into roughly 22,000 different landscape units. Of these, c. 16,000 are bedrock sections. Qualitatively, 41 classes were distinguished, such as

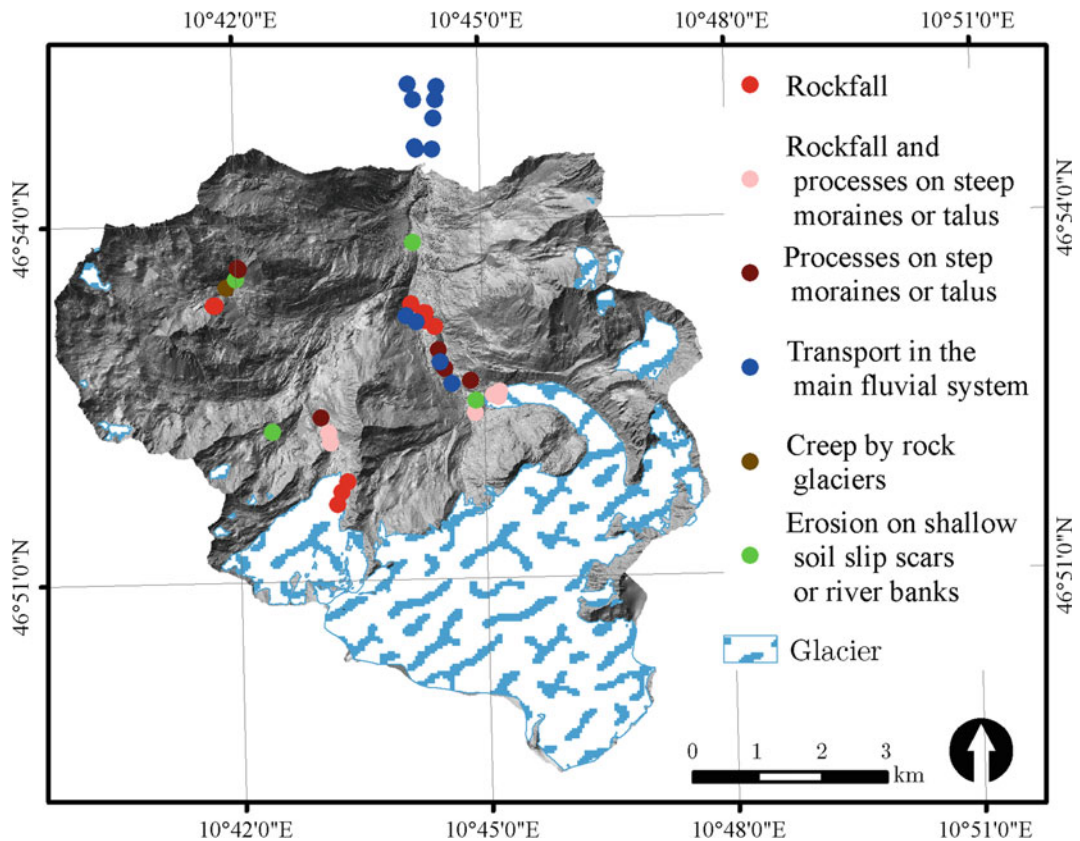


Fig. 17.2 Location of TLS monitoring stations within the study area

units in the active fluvial system (e.g., gravel bars, active channels), glacial storage landforms of two different age-groups (e.g., lateral moraine older than A.D. 1855, ground moraine younger than A.D. 1855), cryogenic landforms (such as rock glaciers of different activity states), bedrock differentiated according to geology, process areas (erosion, transport, and deposition zones of single debris flows), etc. In designing the landform classes, geomorphological maps prepared by others (e.g., Otto 2006) served as a starting point, but classes were further differentiated where it was needed (e.g., separation of moraine ages). The area affected by processes (e.g., debris flows on lateral moraines) was mapped on a multi-temporal basis, using historical aerial imagery (see Sect. 17.4.3).

An example section of the resulting map is depicted in Fig. 17.3. For the sake of clarity, the legend (Fig. 17.4) only contains the class units visible in the depicted area and only landforms. Process areas are not visualized.

Table 17.1 gives the surface percentages of different superordinate landform classes in the Upper Kaunertal. The scale and resulting detail of the geomorphological map implies that sediment balances could be established for landscape units much smaller than the whole catchment (as undertaken for the rockfall part by Heckmann et al. 2016). For the catchment-scale budget presented here, areas related to the single processes were collapsed; thus we obtained the mass of sediment mobilized versus transferred to the main fluvial system at the catchment scale.

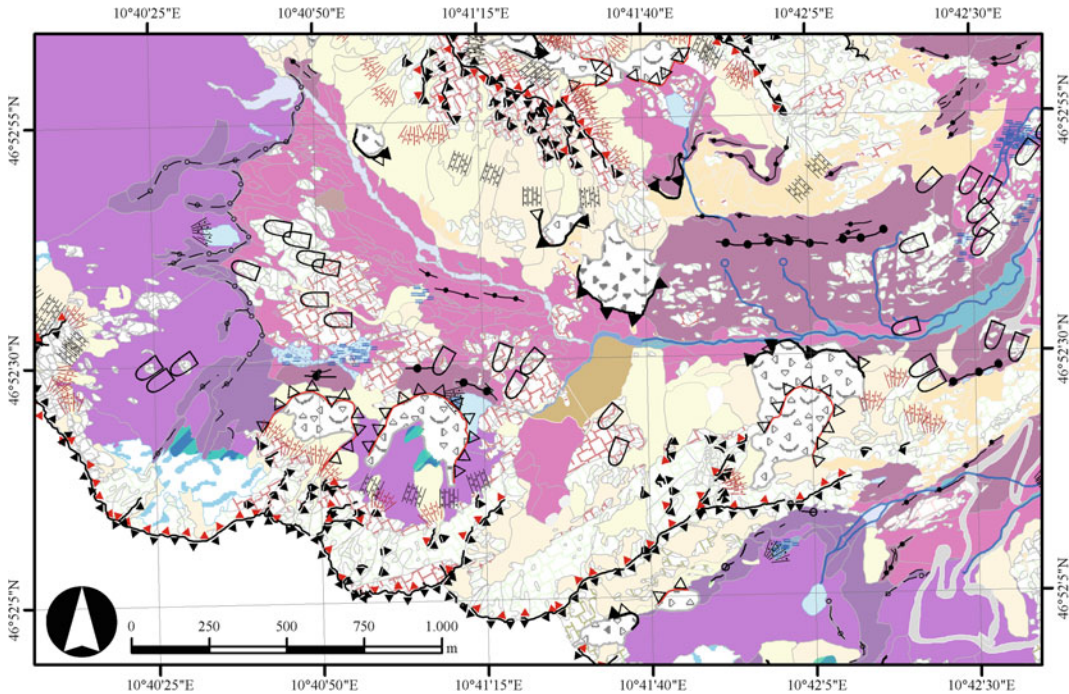


Fig. 17.3 Example section of the geomorphological map

17.4 Process Quantification at the Catchment Scale

With the help of the geomorphological map, a generalized graphical representation of the cascading system (with respect to the relevant processes and storage landforms) was set up (Fig. 17.5).

The process-specific databases, processing and analysis steps taken to obtain sediment transfer estimates will be referred to in the following in dedicated subsections. The treatise will start with mass wasting processes, followed by other hillslope processes and concluding with the construction of the budget using data on glacial processes and fluvial sediment transport in the main channels.

17.4.1 Rockfall

Small-scale rockfall (debris fall) was quantified using both direct measurements of rockfall mass

collected from collector nets and volume change quantification from TLS data (see Chap. 9 for details).

With a total of 14 rockfall rates from the PROSA study area, rockfall production rates in $\text{kg yr}^{-1} \text{m}^{-2}$ were calculated. As the data were acquired using different methods, approaches were slightly different for net-derived and TLS-derived rates. Net-derived production rates significantly depend on the rockwall reference area contributing to the respective nets. This is the main reason why Heckmann et al. (2016) tested three different approaches to obtain the net collector sediment contributing areas (SCA). Here, we used the starting points (and their real surface area computed from the DEM) of modeled rockfall trajectories that ended on the corresponding collector net. To identify potential source cells, a slope threshold of 47.5° was determined using the methodology described in Loye et al. (2009). Rockfall production rates for the TLS-derived mass data were obtained by dividing the collected mass by the real surface

Fig. 17.4 Legend for the geomorphological map (Fig. 17.3)

"Classical" line and point signatures:

- | | | |
|-------------------|---------------|--------------|
| Landforms: | Other: | |
| Talus slope | Source | Whaleback |
| Talus cone | Wetland | Contour line |
| Alluvial fan | Stream | |

Linear morphological features:

- | | |
|-------------------------------|---|
| Crest | Moraine ridge < 10 m (A.D. 1855 or later) |
| Rock glacier front (active) | Moraine ridge > 10 m (A.D. 1855 or later) |
| Rock glacier front (inactive) | Moraine Ridge < 10 m (before A.D. 1855) |
| Rock glacier front (relict) | Moraine Ridge > 10 m (early Holocene) |

Polygon features (landforms):

- | | |
|--|-------------------------|
| Anthropogenic | Talus cone |
| Bedrock: Amphibolite | Talus sheet |
| Bedrock: Augen gneiss | Debris cone |
| Bedrock: Biotite-plagioclase-gneiss | Rock glacier (active) |
| Bedrock: Granitic orthogneiss | Rock glacier (inactive) |
| Bedrock: Granitic porphyry | Rock glacier, relict |
| Fluvial, unspecified | Block slope |
| Fluvial, active main channel | Lake |
| Fluvial, active with gravel bars | Glacier |
| Fluvial, gravel bar | Perennial snow patch |
| Mix glaciofluvial and fluvial sediments | |
| Mix glacial and fluvial sediments | |
| Moraine, unspecified (pre A.D. 1855) | |
| Lateral or terminal moraine (pre A.D. 1855) | |
| Ground moraine (pre A.D. 1855) | |
| Lateral or terminal moraine (post A.D. 1855) | |
| Ground moraine (post A.D. 1855) | |

Table 17.1 Landform coverage

Landform category	Area (km ²)	Percentage
Bedrock	c. 12.92	c. 20.8
Gravitational	c. 6.47	c. 10.5
Periglacial	c. 4.89	c. 7.9
Glacier	c. 19.47	c. 31.4
Glacial	c. 14.02	c. 22.6
Fluvial	c. 1.4	c. 2.2
Anthropogenic	c. 0.84	c. 1.4
Other, mix forms	c. 1.99	c. 3.2

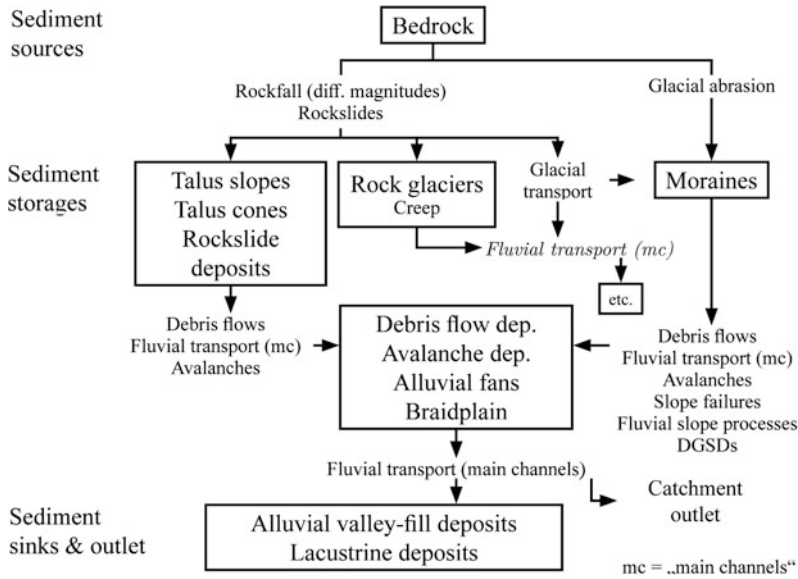


Fig. 17.5 A generalized, conceptual representation of the sediment transport network in the Upper Kaunertal. Relevant processes in italic and (storage) landforms in regular type

area of the bedrock surfaces surveyed with TLS scans and the time interval between samples.

The obtained rockfall rates were used to estimate the parameters of a statistical distribution. A chi-square test, a Kolmogorov–Smirnov test, and a Weibull plot confirmed that a Weibull distribution is suitable to represent this distribution. Figure 17.6 shows this distribution and the rockfall rates obtained with different methods.

In the subsequent modeling step, each identified rockfall source cell in the study area was assigned a rockfall production rate that was drawn from this Weibull distribution. The rockfall produced at each start cell is subsequently distributed downslope via a numerical rockfall model. The model applied has been described in detail by Wichmann and Becht (2005), Wichmann (2006). Since its development, it has been extended to, for example, log modeled trajectories from start to stop cells (Heckmann and Schwanghart 2013). In combination with the geomorphological map (Sect. 17.3), the trajectories were used to set up a graph model of rockfall sediment transfer through the catchment: Raster cells form the nodes that are connected by edges representing potential rockfall trajectories (and their rates of sediment transfer). Nodes (and

the corresponding edges) can be aggregated using the single landforms, or landform types, specified by the geomorphological map (c.f. Heckmann et al. 2016) (Fig. 17.7).

An overall summary of the results, aggregated for each landform type represented in the study area, is presented in Table 17.2. The data reflect the high fragmentation of the complex landscape in high-mountain areas. For example, about 26% of small-magnitude rockfall is deposited on glacier surfaces from where it might be transferred to the proglacial areas and via fluvial transport to the basin outlet. Only 2.6% of debris fall is transferred directly into competent channels of the main fluvial system, and about 18% is blocked by glacial landforms like lateral or ground moraines. Finally, the total debris production sums up to about $25,803 \text{ t yr}^{-1}$.

While the approach discussed above honors all empirical measurement data, a crucial weakness is the lack of a spatial distribution of rockfall rates. This is why a second approach was developed to obtain a study area-wide rockfall sediment budget. To facilitate this approach, Vehling (2016) developed a rock mass stability index and mapped six distinct classes study area wide. As the index had proven to be strongly

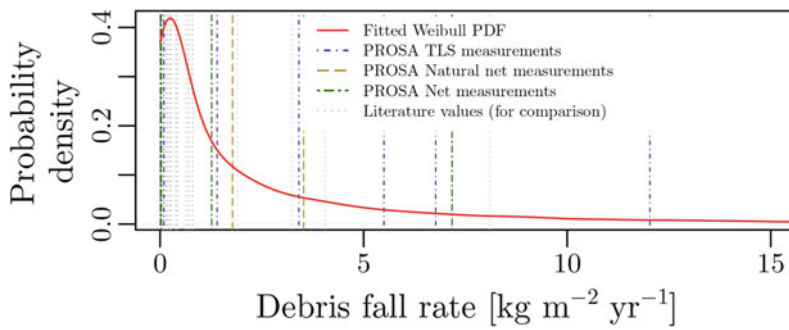


Fig. 17.6 Rockfall production rates and fitted Weibull distribution. Slightly changed, after a figure in Hilger (2017). Values found in other alpine studies are shown for comparison

correlating with rockfall production rates (see Chap. 9), the resulting map could be used in rockfall rate regionalization. However, only rockfall collector net measurements were used to assign rates to the different rock mass stability index classes. While this approach of debris production rate was very different to the one described above, the means of trajectory modeling and analysis was the same.

Using spatially distributed rockfall production rates, a rate of 28,738 t yr⁻¹ (c. 463 t yr⁻¹ km⁻²) was estimated for the whole catchment. This corresponds to a total of geomorphic work performed of circa 1565 W (circa 25.3 W km⁻²). As the use of spatially distributed rates is able to model the true sediment transfer by rockfall more realistically, it is this value that will be used for the construction of the sediment budget in Sect. 17.5.

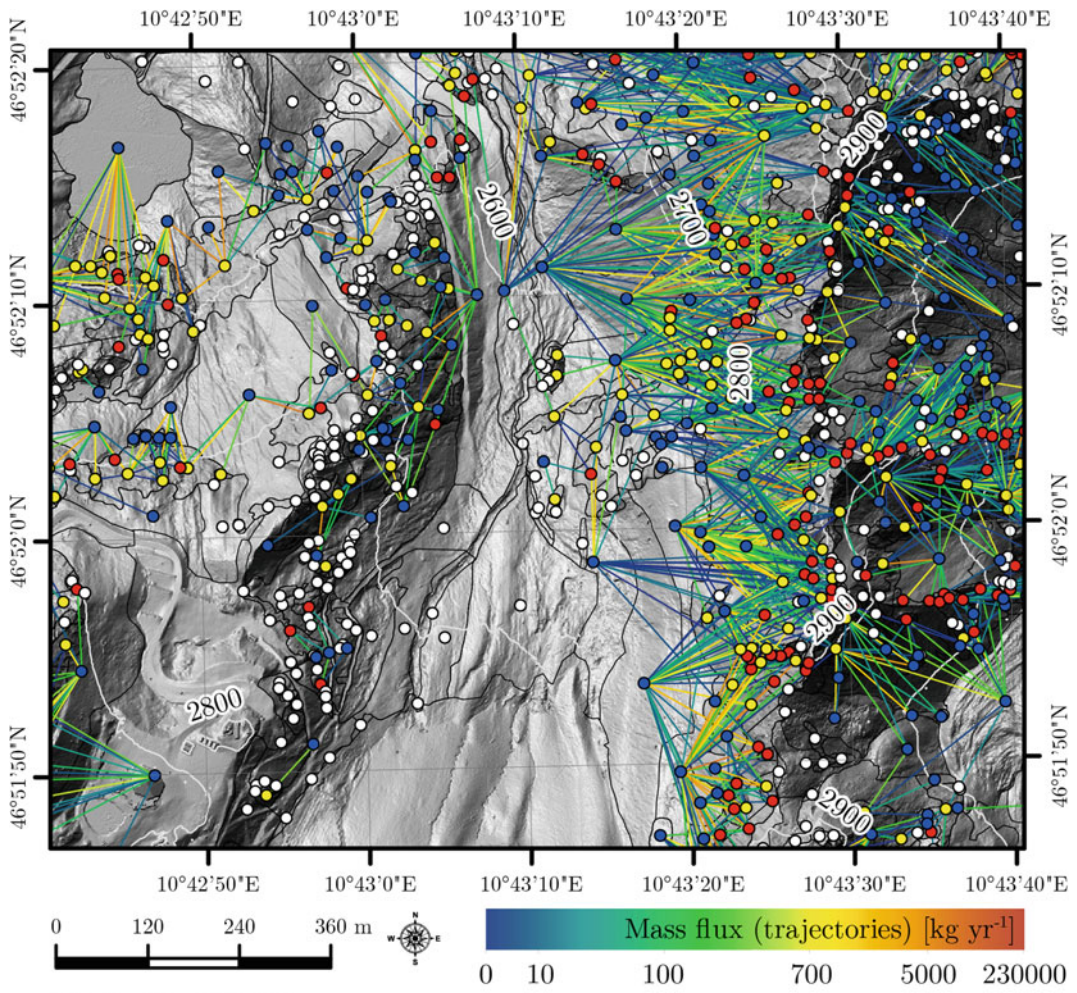
Vehling (2016) reports a related approach to compute the rockfall sediment budget that better honors the spatial factors controlling debris production on rockwalls. He used two different scenarios (one using a simple regionalization of mapped debris fall production rates based on a mapped rock mass stability index, and one using a nonlinear regression function between the index and debris fall production rates) to obtain a sediment transfer rate for debris fall on the whole catchment scale (i.e., not distributed by landforms or landform types). His first scenario gives an estimate of circa 36,400 t yr⁻¹, while the second one yields an estimate of about 46,934 t yr⁻¹. It is evident that Vehling's

estimates are much higher than the one reported above (28,738 t yr⁻¹). The main reason probably is Vehling's use of a lower slope threshold (40° instead of 47.5°) to identify source areas. If we had also used 40° as a threshold (note that we opted for a data-based rather than an arbitrary threshold), a similar total mass as estimated by Vehling would have resulted.

A very detailed documentation of the general work flow presented here, in combination with a discussion of the methodology can be found in Heckmann et al. (2016). Since this publication, several improvements have been made to produce what we consider a more reliable result, for example, the availability of a bigger database (TLS data, longer measurement period at the nets), a further differentiation of the geomorphological map, and the usage of a Weibull instead of a log-normal distribution. Our results are much higher (by a factor of c. 3.5) than the ones published by Heckmann et al. (2016) who used a much smaller database regarding PROSA results and did not apply spatially distributed rockfall rates. The proportions of rockfall sediment delivery to different geomorphic units, however, are fairly consistent, which is due to the use of the same trajectory model.

17.4.2 Rockfall of Higher Magnitude

Sediment transfer rates for rockfalls larger than 100 m³ for the whole study area were presented by Vehling (2016; see also Chap. 9). Vehling



Node classification:

- landform not part of debris fall process area
- source
- link
- sink
- Contours (100 m)
- Landform borders in the geomorphological-geological map

Fig. 17.7 Detail of the debris fall sediment transport network showing the coupling of rockwall sections with individual landforms. Nodes are placed at the centroid

coordinates of each polygon and colored according to their classification as either sediment source, link, or sink

mapped and quantified over 100 rockfalls of this magnitude using ALS data from 2006 to 2012 to arrive at a total sediment transfer rate of c. 111,680 t yr⁻¹, while c. 66,000 t yr⁻¹ must be attributed to the highly active rock slide/rockfall complex at the “Schwarze Wand” (Vehling 2016) above the glacier tongue. It is conspicuous that also a large proportion of rockfalls over

100 m³ fall onto the glacier. Of the remaining c. 45,680 t yr⁻¹, only about 1000 t yr⁻¹ is probably deposited in the main fluvial system (pers. comm. Lucas Vehling 2016), 7640 t yr⁻¹ does not leave the hill slopes, and 37,040 t yr⁻¹ falls onto glacier ice at locations other than the “Schwarze Wand.” The same author has also identified a Bergsturz event (c. 1,000,000 m³) in

Table 17.2 Contribution of low-magnitude rockfall to the sediment budget, unraveled to show sediment delivery to different target landforms or process domains present in the study area in scenario G

Landform target class	Percentage study area	Mass (t yr ⁻¹)	Percentage of total rockfall received	Category	Sum mass for category (t yr ⁻¹)	Percentage total rock received
Bedrock	20.8	1569.37	6.08	Bedrock	1569.37	6.08
Talus sheets	6.4	4397.87	17.04	Gravitational	9662.48	37.45
Talus cones	3.3	4052.83	15.70			
Debris cones	0.7	1211.78	4.70			
Block slope	4.9	610.88	2.37	Periglacial	1724.25	6.68
Rock glacier, not spec	0.1	87.12	0.33			
Rock glacier, active	1.6	569.46	2.21			
Rock glacier, inactive	0.5	161.53	0.63			
Rock glacier, relictic	0.8	295.26	1.14			
Glacier	31.4	6779.22	26.27	Glacier	6779.22	26.27
Gravitational glacial	0.7	601.07	2.33	Glacial	4669.00	18.10
Moraine, not spec., pre-1855	2.7	258.29	1.01			
Terminal/lateral moraine, pre-1855	5.0	331.03	1.29			
Ground moraine, pre-1855	3.3	218.85	0.85			
Terminal/lateral moraine, post-1855	3.7	1078.48	4.18			
Ground moraine, post-1855	7.9	2181.28	8.45			
Active, competent channel	0.3	396.46	1.54	Fluvial	669.34	2.60
Gravel bars, shallow braided channels and fluvial reworked sediments	0.5	57.13	0.22			
Old fluvial storage	1.4	215.75	0.84			
Anthropogenic	1.3	178.84	0.69	Anthropogenic	178.84	0.69
Lakes, not spec., etc	2.7	550.55	2.13	Other	550.55	2.13
Total	100	25803.05	100	Total	25803.05	100

the Riffle Valley, a sub-basin of the Upper Kaunertal. With an estimated age of c. 11,000 yr and a material density of 2.7 t m³, this would imply a transport rate of c. 245 t yr⁻¹. Virtually all of the fine particle size content of the deposit has been transported away since the bergsturz

event at the end of the Egesen stadium (Vehling 2016). Due to this fact and the immense difference in the duration of the time reference period, it is impossible to use the bergsturz sediment transport in the construction of a recent sediment budget of the study area.

17.4.3 Debris Flows

With ALS-based DEMs covering the whole catchment and TLS surveys conducted at a high temporal resolution at the main debris flow-prone locations, debris flow volumes were measured directly using LiDAR data by mapping depositional bodies on DoD. In order to increase the temporal scale, an area–volume relationship was fitted to 62 debris flow deposits, and this relationship was applied to debris flows whose deposits were mapped on historical aerial photos (for details, see Hilger 2017). In summary, the deposits of 199 debris flows that occurred within the time period 1954–2014 were quantified.

The fact that about 75% of all debris flows detected and quantified for the time period from 2006 on occurred within the proglacial areas of either Gepatsch or Weißsee glaciers underlines the relevance of this process in areas of recent deglaciation (Damm and Felderer 2008; Legg et al. 2014). Depending on the time period chosen as a reference, mass transfer by debris flows in the Upper Kaunertal is between 704 t yr^{-1} (1954–2014, using both measured and estimated debris flow volumes) and 1790 t yr^{-1} (2006–2014, including only those debris flow volumes that were measured using DoD).

The total mass determined is highly dependent on the area–volume relationship used. Ordinary bootstrapping (Canty and Ripley 2016) revealed a standard error of roughly 3600 t (58 t yr^{-1}), or circa 8% of the total sediment transfer estimated for the time period AD 1954–2014.

The measurement of debris flow deposits alone makes it difficult to analyze the proportion of debris flow sediment that has entered the fluvial system. Therefore, we computed budgets (i.e., erosion and deposition volumes) for those debris flows that had reached the fluvial system (as indicated by the spatial pattern of the DoD) in order to obtain the volume of the debris flow that has left the hillslope subsystem. This revealed that, during the years 2006–2014, hillslope-type debris flows transferred a minimum of 455 t of sediment to the fluvial system. The corresponding delivery rate of 62 t yr^{-1} amounts to only 3%

of the debris flow volume measured within this period on the catchment scale. On the hillslope scale, however, the proportion of sediment delivered to the channel network can be extremely variable. Haas et al. (2012; see also Chap. 11), for example, report 9 and 59% for two different sections of a lateral moraine in the Kaunertal.

17.4.4 Deep-Seated Gravitational Slope Deformations and Rock Slides

While debris flows are comparatively effective in transferring sediment to the main fluvial system, rock slides and deep-seated gravitational slope deformations (DGSDs) only have an indirect impact on the contribution of hillslope processes to the main fluvial system. Vehling (2016) has identified several of such moving sediment complexes in the Upper Kaunertal, although only some of them show measurable movement rates. Notable DGSDs are located at the Nörderberg mountain and the Kühgrube Valley (Fig. 17.1). While the latter one is rather small (circa $160,000 \text{ m}^3$) and shows very little activity, the former is of interest concerning sediment transport in the study area as shallow soil slips have developed on its surface. These, in turn, provide material to the large Fernnergries avalanche(s) that are capable of transferring sediment to the main fluvial system (Sect. 17.4.5). This is an example of how DGSDs are relevant in preparing material for follow-up processes. The currently moving body has a volume of about $300,000 \text{ m}^3$ and moves at velocities of about 5 mm yr^{-1} (Vehling 2016). The sediment transfer by the other rock-slides and DGSDs located in the study area could not be quantified.

17.4.5 Avalanches

It has been repeatedly shown that some avalanches not only transport snow, but also other materials like vegetation and sediment (e.g., Jomelli 1999; Heckmann et al. 2002; Freppaz

et al. 2010; Ceaglio et al. 2010; Korup and Rixen 2014). Especially full-depth avalanches and slush avalanches occurring late in winter or early in spring are relevant here (Saemundsson et al. 2008). In the Upper Kaunertal, observations indicate that also surface layer avalanches transport sediment. They do so by flowing through bedrock gullies (Moore et al. 2013) and across hill slope areas already snow-free in early spring (Luckman 1977), or by removing debris that fell onto the snow surface during winter (Jomelli and Bertran 2001). For simplicity, we use the term “sediment transporting avalanche” in this study to refer to all types of avalanches relevant for sediment transport.

Fieldwork for avalanche sediment transport quantification was conducted during the snow melt period (late May and early June of 2013 and 2014) as this is the main time during the year when relevant avalanches are occurring (Gardner 1983; Baggi and Schweizer 2009; Näher 2013). Due to safety concerns, not all parts of the catchment could be mapped for avalanches each spring. As a result, values were extrapolated for the whole catchment based on the mapped area and the mass on this area. Mapping and sampling were undertaken as soon as sediment was found concentrated on top of pure snow on avalanche accumulation bodies, but before signs of significant lateral melting were present.

Mapping was accomplished in a scale of about 1:2500. Following André (2007), Jomelli and Bertran (2001), and Sass et al. (2010), six sediment cover classes were chosen for sediment mapping on avalanche bodies. Except for a self-contained class representing bare snow without any sediment cover (class 0), five equidistant classes representing a sediment cover from >0–20% (class 1) to 80–100% (class 5) were defined for mapping and sampling. Examples of each of the different classes are depicted in Fig. 17.8. As an example, Fig. 17.9 shows a map of two large sediment transporting avalanches recurring every year on the western moraine above the Fernergries.

Sampling plots for the different coverage classes were 0.25 m² most of the time (cf. areas delineated by metering rules in Fig. 17.8).

Sampling plots were placed randomly within the sediment covered part of an avalanche deposit by blindfolded throwing the metering rule from uphill onto the surface (c.f. Korup and Rixen 2014). As it was not possible to sample the whole snow column below any sampling plot, it cannot be ruled out that some sediment was lost to quantification this way. Investigations by Bell et al. (1990), Heckmann et al. (2002), and Heckmann (2006) have shown that, on average, about 6.6% ($s = 6.2\%$, $n = 16$) of the mass found on top of such sampling plots is found within the snow body below the surface.

The thickness of the sediment layer varied between 0 and 70 mm (Näher 2013). This is an additional potential source of error, as the percentage of surface cover mapped might be very high and the sediment thickness is comparatively low. It could be observed multiple times that surfaces appearing very dark from afar had only a very thin cover of small-size particles (Näher 2013). All sediment found within a sampling area was collected and taken to the laboratory for drying and weighting. Boulders and cobbles (>64 mm) were weighted in the field using a digital scale to reduce transport effort from sampling sites difficult to access. In total, 20 sampling sites were evaluated in 2013 and 40 sampling sites in 2014. The distribution of the sampling plots over the cover classes and the average sediment mass for each class is shown in Table 17.3.

The very broad confidence intervals reflect the issue of both different sediment thicknesses and the limited number of sampling plots available. The lower limits of zero for classes three and four are certainly not realistic as these classes appear rather dark and definitely contain quite some sediment. However, further samples are necessary to narrow down the interval.

Most avalanches do not transport sediment to localities where material can be re-mobilized by other processes (cf. below for one exception). The total mass moved by sediment transporting avalanches in the Upper Kaunertal is substantial. Taking the results from the winters of 2012/2013 (Näher 2013) and 2013/2014 (Rumohr 2015), an average of 12.6 t km⁻² was moved by avalanches. This corresponds to a total mass of

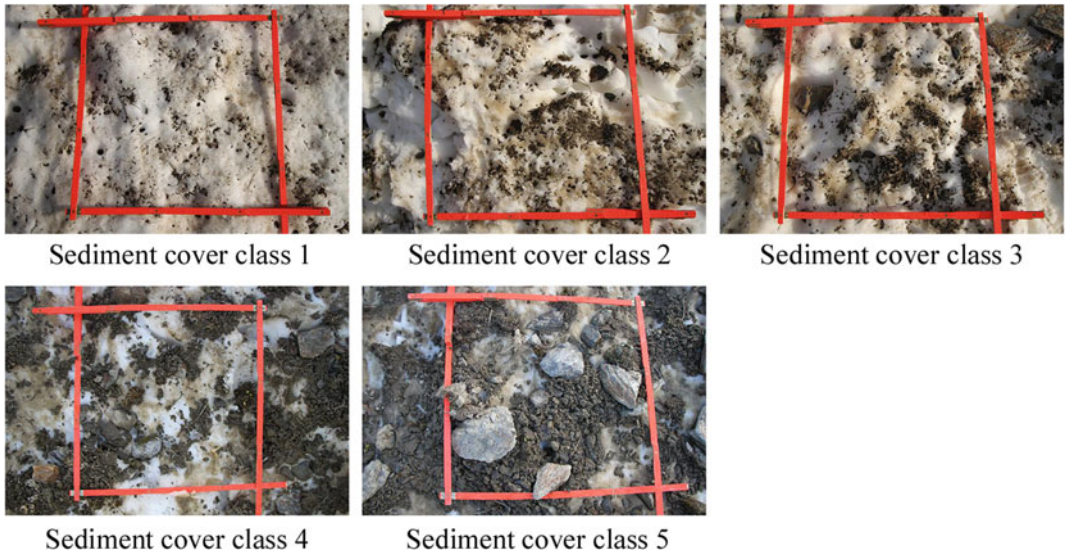


Fig. 17.8 Examples of sampling plots representing the different sediment cover classes

Fig. 17.9 Sediment cover classes mapped on the two large Fernergries avalanches in spring 2014. Figure taken from Hilger (2017)

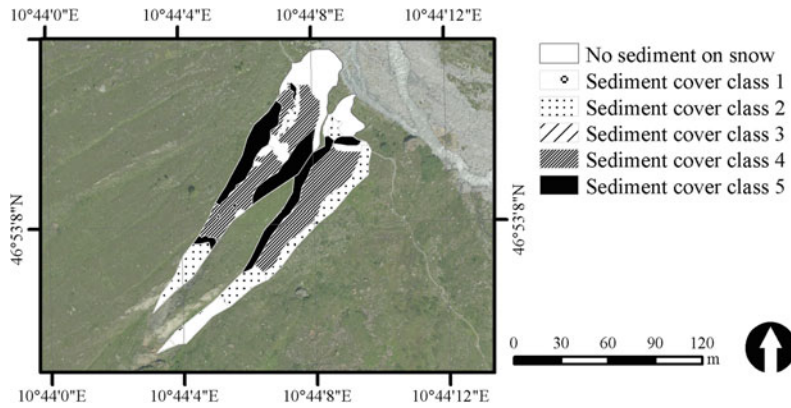


Table 17.3 Average weight contained on 1 m² of each sediment cover class in winter 2013/2014

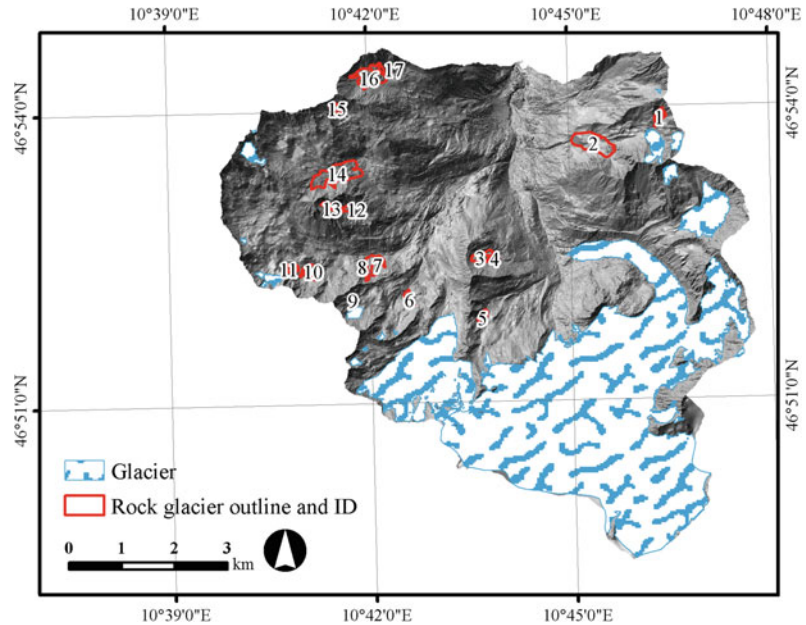
Sediment cover class	Average weight (kg m ⁻²)	Number of plots	Confidence interval (kg m ⁻²) ^a
One (0–20%)	0.54	11	[0.11,0.97]
Two (20–40%)	1.09	12	[0.56,1.6]
Three (40–60%)	7.06	5	[0,15.8]
Four (60–80%)	5.5	5	[0,12.1]
Five (80–100%)	18.8	6	[6.33,31.2]

^a95% confidence level

sediment transported by avalanches in one year of c. 781 t. Only a very small portion of this amount entered the fluvial system as most

avalanches act on the hill slopes of tributary valleys with broad valley bottoms (such as the Riffle Valley or Krummgampen Valley). Only

Fig. 17.10 Location of the 17 active rock glaciers in the Upper Kaunertal



one avalanche reached the fluvial system directly; this avalanche, however, has moved quite a significant amount of sediment from the 1855 lateral moraine (and parts of the hillslope above) into the fluvial system: Visual inspection of the outline and sediment cover classes over the gap created by the Faggenbach through the avalanche deposit yields a mass of 13.46 t delivered by the avalanche to the fluvial system in the winter of 2012/2013. Only the results from two winters were used in the calculation of the result presented above. Considering the very high temporal variability of avalanches in general and in the study area (Luckman 1977; Näher 2013), this is a very short time to assess the contribution of avalanches reliably and adds to the uncertainty of the estimate together with sampling strategy weaknesses and inaccessibility of some parts of the study area (see above). Based on an interview of a local avalanche expert, Näher (2013) reports that the winter of 2012/2013 was a “normal” avalanching winter, i.e., “normal” in comparison to historic winters. This interannual variability, however, has a severe impact on the number of avalanches in the Upper Kaunertal and the two winters before 2012/2013 were seen as under average in terms of avalanche activity (Näher 2013).

17.4.6 Creeping Permafrost by Rock Glaciers

Before measurements began, it was already clear that sediment transport by rock glaciers directly to the fluvial system is very low in the Upper Kaunertal. Sediment transfer by rock glaciers is therefore mainly important for internal sediment turnover.

For an estimation of sediment transfer by rock glaciers, both sediment mass and velocity had to be determined. Sediment mass was estimated based on rock glacier extent mapping, thickness estimation via frontal height measurement and sediment percentage estimates (Neugirg 2013). Mean annual displacement rates for the time from 2006 to 2012 were estimated using feature tracking on DTM-derived hill shade grids for each rock glacier (cf. Scambos et al. 1992; Kaufmann and Ladstädter 2003; Dusik et al. 2015; Chap. 7). Seventeen rock glaciers were identified for sediment transfer analysis in the Upper Kaunertal. Figure 17.10 gives an overview of their locations.

The estimation of rock glacier mass yielded values between 0.25 and 22.63 Mt, assuming a sediment content of 40% (Gärtner-Roer 2012). Displacement rates ranged from 0.09 to

0.44 m yr⁻¹ (see Neugirg 2013; Hilger 2017) for a breakdown of the single rock glaciers.

In summary, a total mass of 52.92 Mt (0.25–22.63 Mt for individual rock glaciers) is currently contained in rock glacier bodies in the Upper Kaunertal. These move, on average, with a speed of 0.17 m yr⁻¹ (0.09–0.44 m yr⁻¹ for individual rock glaciers) at the surface. Using the measured annual average horizontal displacement rates at the surface, height and width of each rock glacier body and, again, assuming a sediment content of 40% and a density of 2.69 t m³ (Hausmann et al. 2012), the total sediment transfer of all 17 rock glaciers in the study area was estimated at c. 21,497 t yr⁻¹. Nothing is known about the velocity reduction with depth within the different rock glaciers; therefore, our quantification under the assumption of a constant creep velocity equal to the surface velocity is very likely an overestimation.

All rock glaciers except one are located too far from the active fluvial system as to directly deliver sediment. In the Krummgampen Valley, a rock glacier is adjacent to the channel, and historical imagery from 1997 shows sediment from the rock glacier having advanced into the channel, with the river flowing through and under the blocks of the rock glacier. It is impossible, however, to estimate the amount of sediment mobilized. Due to the small channel gradient at this location, it probably is very low, and the total amount is probably negligible in comparison to other processes.

17.4.7 Slope Wash and Linear Erosion on Hillslopes

Slope erosion by surface runoff on hill slopes occurs as sheetwash, linear (rill or gully) erosion, or piping (in the subsurface). In comparison to other processes, they have the ability to connect sediment sources relatively far above the main channels to the main channel network.

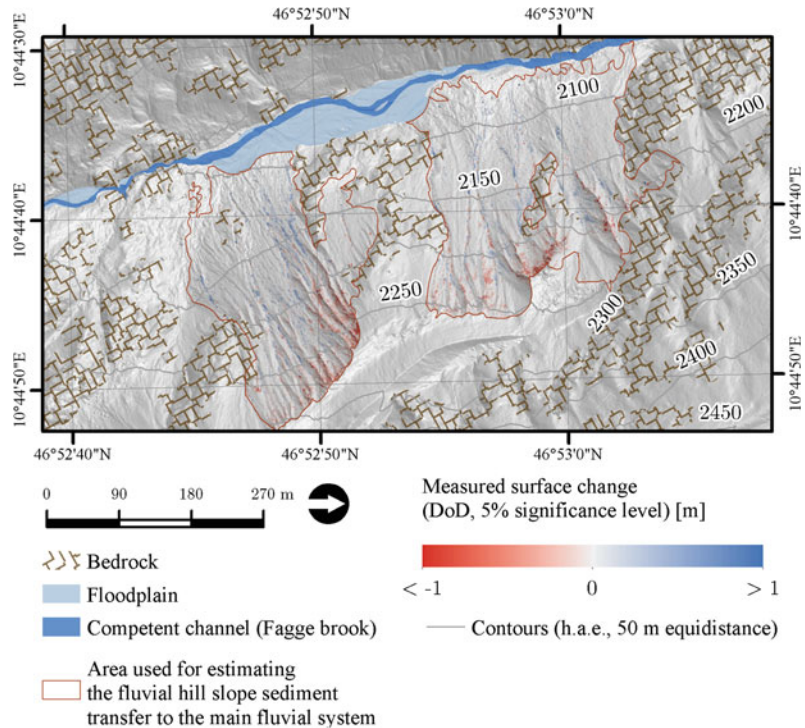
The net sediment balance of these processes was measured using DEMs (July 4th, 2012; July 18th, 2014; resolution 0.7 m) on the steep lateral moraines. A spatially distributed LoD with a

mean of 0.08 m was applied. Figure 17.11 shows a thresholded DoD of the true right lateral moraine of Gepatsch Glacier. The net balance of the slope is 1837 t (using a density of 2.2 t m⁻³). As just above 400 t have been moved from the slope to the main fluvial system via debris flows during the same time period (c.f. Sect. 17.4.3), it can be concluded that circa 1400 t were transferred to the Fagge river by processes other than debris flows.

A ratio of sediment transported by debris flows versus slope-aquatic and fluvial processes of 1:3.7 can be estimated for the AD 1855 true right lateral moraine of Gepatsch Glacier. It is well possible that some deposition that has occurred on the lower parts of the lateral moraine was not accounted for, and that the true amount of sediment having reached the Fagge river by fluvial transport is higher, because accumulation bodies by fluvial transport are typically spread out and of low height and therefore difficult to detect using DoD. Estimating the contribution of fluvial hill slope erosion to the main fluvial system at only one location in the study area is probably underestimating the total value. It is possible that the true right 1855 lateral moraine of the Weißsee Glacier, for example, is coupled to the upper reaches of the Riffle River during high intensity rainstorm events. As this river passes significant depositional areas downstream, however, it is improbable that much of this sediment reaches the Fagge river. In addition, an unvegetated moraine slope at the true left side of the Upper Fagge river valley (just below the Gepatsch Glacier snout) is close enough to the main fluvial system to contribute sediment. The slope, however, is very small. Nevertheless, the value reported above should therefore be regarded as a minimum value.

Sediment transport also occurs in small channels on vegetated hill slopes. Transport rates measured in sediment traps, however, were relatively low (mean: 5.82 t km⁻² yr⁻¹) in relation to the sediment transport on the lateral moraines bare of vegetation (5830 t km⁻² yr⁻¹). These results support the results by Becht (1995), who showed that fluvial transport on non-vegetated moraine material is about 1000 times higher than

Fig. 17.11 Erosion and accumulation on the true right lateral moraine of Gepatsch Glacier. Figure taken from Hilger (2017)



on other surfaces. The same author reported that fluvial erosion is about 90% lower in vegetated moraines than on unvegetated ones in the Pitz Valley.

It is for the above-mentioned reasons that the value of circa 700 t yr^{-1} obtained via DEM differencing on an area of 0.12 km^2 on the AD 1855 Gepatsch Glacier lateral moraine can be regarded as representative for the sediment delivery to the main fluvial system in the study area.

17.4.8 Sediment Transport in the Channel Network

For the construction of the sediment budget, fluvial sediment transfer measurements at two locations are important: (i) at the glacier snouts and (ii) at the basin outlet. More information on the methodology of these measurements can be found in Chap. 13. Measurements of both bed and suspended load were undertaken at the Gepatsch Glacier snout during the ablation

periods of 2012, 2013, and 2014 on an average of c. 96 days per year. The obtained measurements were used to calculate an average daily transport rate of c. 52 t day^{-1} for bed load and c. 173 t day^{-1} for suspended load. Taking the months May to October (184 days) as the period of significant fluvial transport through the glacier snout, a total rate of glacialfluvial sediment of $41,401 \text{ t yr}^{-1}$ was estimated.

Long-term sediment yield (=export from the catchment) was computed by morphological budgeting using pre-reservoir and recent DEMs of the delta building up in the Gepatsch reservoir at the catchment outlet. The pre-reservoir DEM was reconstructed from a photogrammetric analysis of aerial photos taken in 1953. Terrestrial LiDAR surveys were possible as the lake level is very low every May, exposing a delta at the mouth of the Fagge river into the reservoir (see scan positions north of the study area in Fig. 17.2). In addition, data from a TLS survey conducted in November 2015 by TiWAG (Tiroler Wasserkraft AG) were available for balancing. The obtained overall levels of

detection and the balances obtained for the investigated time periods 1954–2015, 2012–2013, and 2013–2015 can be found in Table 17.4.

On August 25/26, 2012, heavy rain presumably triggered the rupture of a water pocket in or below the glacier tongue. The ensuing flood (max. discharge $47.3 \text{ m}^3 \text{ s}^{-1}$) deposited c. $90,000 \text{ m}^3$ of sediment in the lower proglacial area (e.g., the Fernergries braidplain), while our measurements indicated that only c. $70,000 \text{ m}^3$ were removed from the upper proglacial area. The difference, about $20,000 \text{ m}^3$, must have been delivered from (sub-)glacial sources (Baewert and Morche 2014; Stocker-Waldhuber et al. 2017).

Using the pre-reservoir and 2015 DEMs, the delta volume is estimated at $194,701 \text{ m}^3$, representing an annual rate of $3192 \text{ m}^3 \text{ yr}^{-1}$ (6384 t yr^{-1} assuming a bulk density of 2 t m^{-3}). The annual rate during 2012–2013 is in the same order of magnitude as the long-term average. During three ablation seasons (2013–2015), however, $73,254 \text{ m}^3$ (on average $24,418 \text{ m}^3 \text{ yr}^{-1}$ or $48,836 \text{ t yr}^{-1}$) of sediment were deposited in the delta. Two observations follow from these numbers: First, the sediment volume transferred to the delta since the 2012 flood corresponds to almost 80% of the material deposited on the floodplain during the event; together with the fact that the annual sediment output from the glacier 2012–2014 ($41,401 \text{ t yr}^{-1}$) is similar to the annual yield of $48,836 \text{ t yr}^{-1}$ at the catchment outlet (years 2013–2015), this highlights the fact that the longitudinal sediment connectivity in the Fagge river system has been comparatively high after the flood. Second, almost 40% of the delta volume can be attributed to the (reworked) sediment mobilized by the 2012 event, emphasizing the exceptional character of this event, and supporting Warburton's (1990) conclusion that large magnitude, low frequency flood events are the dominant control of sediment transfer in the proglacial zone.

Tschada and Hofer (1990) applied specific sediment transport rates measured at the Taschach and Pitz rivers between the years 1964 and 1989 to the Fagge river, estimating the total

annual sediment yield to the delta at $58,340 \text{ m}^3 \text{ yr}^{-1}$ ($45,930 \text{ m}^3 \text{ yr}^{-1}$ suspended load, $12,410 \text{ m}^3 \text{ yr}^{-1}$ bedload). As these authors used the total catchment area of the Gepatsch reservoir (107 km^2) instead of that at the inflow (62 km^2) for their estimation, we corrected their results by a factor of $62/107$ and get a rate of $33,804 \text{ m}^3 \text{ yr}^{-1}$ ($26,613 \text{ m}^3 \text{ yr}^{-1}$ suspended load, $7192 \text{ m}^3 \text{ yr}^{-1}$ bedload). Using a density of 1.8 t m^{-3} , the suspended load is estimated at c. $47,900 \text{ t yr}^{-1}$, which is more than double the value of $22,267 \text{ t yr}^{-1}$ that we determined for suspended load in the period 2012–2014. On the one hand, our results have to be regarded as a minimum estimate, as TLS surveys could not cover the complete delta. As we estimated bedload transport by comparing the suspended sediment transport measured in the Fernergries to the TLS survey in the fan of the reservoir, the true total mass of bedload is probably higher. On the other hand, our data are measurements, while Tschada and Hofer (1990) report an estimation based on transferring measured data from neighboring catchments to the Fagge river. Furthermore, while delta deposition from tributaries of the reservoir located further north can be considered negligible, it is possible that an unknown quantity of sediment from the Pitz valley water diversion (bedload, however, is fully retained by a Tyrol weir at the water intake) is included in our balance, as water from the Pitz diversion enters the reservoir just north of the area that could be surveyed by TLS.

17.5 Results and Discussion: The Sediment Budget of the Upper Kaunertal

For the establishment and closure of the Upper Kaunertal sediment budget, only data on glacial processes and mobilization of sediment by the main channels are missing.

The sediment balance of the glaciers in the study area is not known as it is impossible to measure the erosional work at the glacier basis. The sediment mass flux and its changes through the glacier tongue of Gepatsch glacier were

Table 17.4 Results of the sediment yield quantification efforts using point cloud data of the Fagge river delta in the Gepatsch reservoir

Time period	LoD (1) (m)	Volume (m ³ yr ⁻¹)	Mass (t yr ⁻¹)
1954–2015	0.44	c. 3191	c. 6383
2012–2013	0.12	c. 2404	c. 4808
2013–2015	0.12	c. 24,418	c. 48,836

The period 2013–2015 included the summers of 2013, 2014, and 2015 and was therefore regarded as representing three ablation seasons

Table taken from Hilger (2017)

measured using a variety of methods. Using data from Stocker-Waldhuber et al. (Chap. 5), the sediment production of Gepatsch Glacier is estimated at 1700–170,000 t yr⁻¹, which is consistent with the measured glacialfluvial sediment transfer of 41,401 t yr⁻¹. No information is available on the masses deposited as moraines in the forefield to this date. Also, no data are currently available for glaciers other than the Gepatsch glacier, which is why the sediment budget of the Upper Kaunertal remains incomplete concerning the sediment transfer from glaciers. Bringing together the results for the different processes treated in the previous sections, the Upper Kaunertal sediment budget is presented in Fig. 17.12.

The main fluvial system is represented as a thick arrow. The contributions of other processes are indicated by black lines of varying thicknesses indicating their relative importance. Processes are labeled in small caps, with time periods the values refer to added in brackets. Values next to a circular arrow represent internal sediment transfer, that is the amount of sediment redistribution on storage landforms without delivery to the main fluvial system. It is typical of sediment budget studies that their results are associated with high uncertainties, especially in catchments displaying a high relief and topographic heterogeneity (Sanders et al. 2013). This holds true even more when the studied catchment is comparatively large and processes are studied only for a few years (as in this study). This is why the sediment budget requires discussion.

The first fact that is conspicuous from looking at the sediment budget is that hill slope processes contribute only a fraction of the total mass of sediment exported from the catchment. As

already mentioned, the extreme event in August 2012 left its mark in the high amount of sediment eroded from the river banks. An estimation via ALS DEM differencing yielded a mass of circa 8250 t yr⁻¹ having been mobilized between the summers of 2012 and 2014 in this way. It has been observed that much of this sediment has been deposited just downstream of the locations it has been mobilized from. However, it is unknown which portion of the mobilized mass has been transported through to the outlet in relation to material of other origins. The remaining discrepancy of the sum of processes versus the total export is indicative of a high fluvial sediment delivery from below the glacier.

One source of error independent from the uncertainties of single process estimates is the anthropogenic modification having taken place during the measurement period in the Upper Kaunertal. Sediment has been transported by human action on a regular basis at various locations: Sediment has been excavated from the floodplain just below the Fernergries bridge, from the delta apex at the reservoir and from the proglacial area of the Weißsee Glacier. It is unknown where the sediment has been transported to in all cases.

Rockfalls of different magnitudes are dominating the sediment transfer in the study area, followed by rock glacier transport, fluvial transport in the main channels and debris flows. The importance of glacial processes is very high, although a precise value cannot be given. Avalanches transport a substantial amount of sediment but cannot compete with other processes, while shallow soil slips seem to have ceased activity in recent years. Overall, sediment transfer in the main fluvial system is of greater

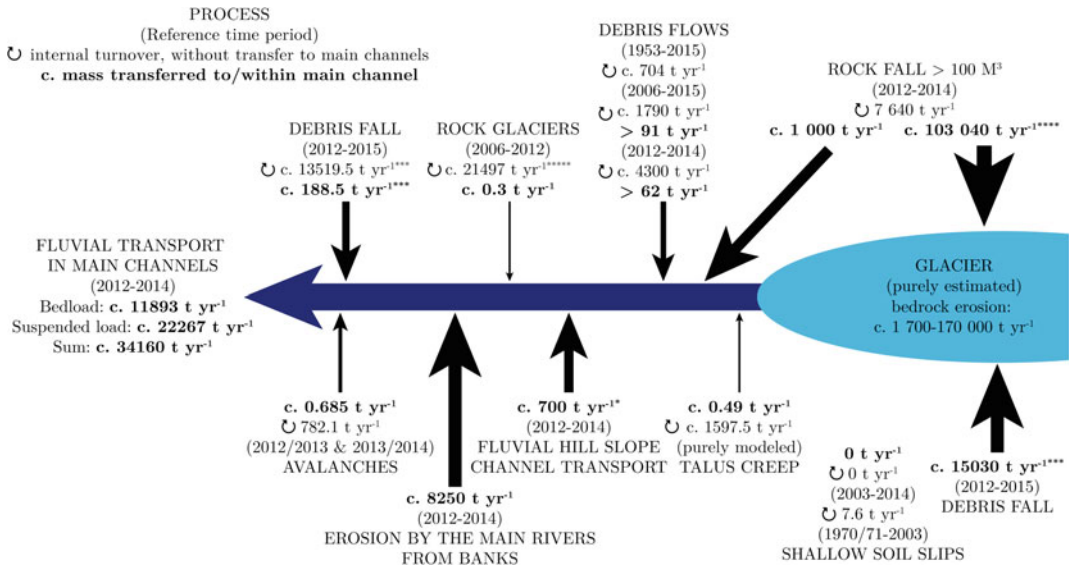


Fig. 17.12 Representation of the Upper Kaunertal sediment budget. Figure adopted from Hilger (2017)

importance to the total amount of sediment exported from the catchment than all hill slope processes combined, which is mainly the result of transport of sediment flushed from below the snout and mobilization from the banks (especially during the extreme event).

Because of their long recurrence intervals, bergsturz events are of minor importance among rockfall processes in the study area. This result is different to what both Krautblatter et al. (2012) and Caine (1986, cited in Vehling 2016) reported from their study areas. Krautblatter et al. (2012) stated that bergsturz events, followed by rockfall <math><10\text{ m}^3</math>, are of greatest importance in the Rein Valley, Northern Calcareous Alps. The importance of bergsturz events in the Rein Valley, however, is caused by large distances between joints in otherwise compact rock making up the high and very steep rockwalls. For the Upper Kaunertal, Vehling (2016) concludes that although extreme magnitudes are less effective than smaller ones, it is “extreme locations” that are very important: The “Schwarze Wand” rockslide complex is a source of small-magnitude rockfall releasing about two times the total mass of what is mobilized at all other rockwalls combined. A dominance of rockfall of small

magnitudes is also reported by Sanders et al. (2013). As Vehling (2016) correctly states, however, this could be the result of the short measurement/reference period their results refer to.

Studies that have compared the relative importance of different geomorphic processes in high-mountain areas are rare. Warburton (1990) determined the relative importance of different processes in the proglacial area of Bas Glacier d’Arolla. As his measurements were conducted only for a short time during the 1987 ablation season, they are not directly comparable to the result obtained in this study, based on a monitoring program spanning several years (no data on avalanche sediment transport are available from Warburton 1990, for example). In general, however, the results seem to complement one another: Warburton has found transport in the channels dominating the sediment transfer in his study area, followed by hillslope processes (including rockfall) and slope wash being of minor importance. Beylich (2000) gives a ranking of many geomorphic processes following their relative importance in terms of total mass transfer (i.e., independent to the respective contribution to the main fluvial system) in Austdalur, East

Iceland, ranking aquatic slope denudation first, followed by geochemical denudation, avalanches, debris and boulder falls, talus creep, debris slides, and flows and deflation. This is very different to what has been found in the Upper Kaunertal. Reasons include, among others, the relatively low relief in Beylich's study area (which relates to the occurrence of comparatively few rockwalls), the absence of a glaciers (and corresponding land forms), and rock glaciers. In addition, a much larger percentage of the Austdalur study area is vegetated.

In general, hillslope-channel coupling in the study area is poor; this implies that only a small amount of material is transported directly from sediment storages on the slope to the main channels. A look at the sediment budget (which also gives internal sediment transfer/mobilization rates) reveals that while about 34,160 t yr⁻¹ have left the catchment between 2012 and 2014, about 50,000 t yr⁻¹ were mobilized but did not reach either the glacier or the main fluvial system. As sediment export 2012–2014 is much higher than the long-term average, and as an additional 120,000 t yr⁻¹ of rockfall were deposited on glacier ice, often far from the main fluvial system, it becomes evident how disconnected the sediment transport system in the Upper Kauner Valley really is unless an extreme event occurs. Comparing the total rate of sediment mobilization (almost 180,000 t yr⁻¹) and an assumed export rate of about 7000 t yr⁻¹ (educated guess based on the long-term average, excluding the 2012 extreme event), it is clear that only about 4% of all sediment moved in the study area reaches the outlet. This is not untypical for glacial valleys, as their broad valley bottoms often lead to a decoupling of the main fluvial and hill slope subsystems. Similar results are reported by Beylich et al. (2011) from Erdalen, Norway or Austdalur, Iceland. Not many studies have tried to establish a sediment budget for meso-scale catchments or have even quantified more than one sediment transferring process in such a catchment. In addition to the ones discussed in Chap. 8.1, Vorndran (1979) (cited in Becht 1995) has established a mass balance for the Sextner river catchment in Southern Tyrol but has not

differentiated between different processes. Becht (1995) quantified different geomorphic processes in the Eastern Alps.

The authors believe that the presented results are a good step forward in quantitatively investigating sediment transport of all relevant processes and can serve as a reference for future research. Maybe, the Kaunertal can become a type locality for sediment budget studies of high-mountain meso-scale catchments.

Acknowledgements The measurement of different processes in a high-mountain area over a time period of several years is a demanding task. In addition to the authors, several student assistances provided very valuable help and support in the field, performed analysis in the laboratory, helped in mapping efforts, and even produced intermediate results. Especially mentionable is the field and laboratory work as well as mass calculations for avalanches by Martin Näher and Phillip Rumohr. Important results on rock glacier movement have been provided by Philip Neugirg, while Florian Riehl worked with data from the sediment traps in hillslope channels. Other student assistants the authors would like to thank are Sarah Betz, Stefan Löser, Sebastian Wiggerhauser, Hendrik Hövel, Kerstin Schlobies, Arnt Luthart, Anne Schuchardt, Matthias Faust, Martin Weber, Eric Rascher and Karolin Dubberke, Alexander Bryk and Shannon Hibbard.

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