Sediment Yield and its Interannual Variability are Underestimated in Supply-Limited Mountain Basins with Short Records

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Abstract

Climate and sediment supply are critical factors for the sediment output of geomorphic systems. It is known that non-linearities between forcing and sediment mobilization may lead to dampened or shredded environmental signals in sediment flux measurements. But it is unclear under which circumstances environmental signals, such as extreme events or climate change, are transmitted and measurable downstream. We used a sediment cascade model and a stochastic weather generator to quantify climate forcing effects under a range of sediment supply regimes in a debris-flow catchment in the Swiss Alps (Illgraben). Sediment yields estimated from short records have high uncertainties both in terms of mean and interannual variability, and tend to be underestimated especially in supply-limited systems, where also long-term memory effects driven by sediment storage are evident. Consequently, climate change impact assessments based on short duration records may be grossly inaccurate, and should be extended with uncertainty estimation.

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Key Points:

- Long-term sediment flux simulations (10k years) at hourly resolution are studied under stochastic forcing
- Sediment yield estimates from short records are highly uncertain and likely underestimated
- The actual timing of sediment input events is not preserved in the sediment yield

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Abstract

Climate and sediment supply are critical factors for the sediment output of geomorphic systems. It is known that non-linearities between forcing and sediment mobilization may lead to dampened or shredded environmental signals in sediment flux measurements. But it is unclear under which circumstances environmental signals, such as extreme events or climate change, are transmitted and measurable downstream. We used a sediment cascade model and a stochastic weather generator to quantify climate forcing effects under a range of sediment supply regimes in a debris-flow catchment in the Swiss Alps (Illgraben). Sediment yields estimated from short records have high uncertainties both in terms of mean and interannual variability, and tend to be underestimated especially in supply-limited systems, where also long-term memory effects driven by sediment storage are evident. Consequently, climate change impact assessments based on short duration records may be grossly inaccurate, and should be extended with uncertainty estimation.

Plain Language Summary

Whether or not climate change is measurable in the sediment output of a basin is a timely question. Climate has an important role for processes related to sediment production and transport. However, because relations between these are complex and often non-linear, it is questionable if environmental signals such as climate change are also transmitted and measurable in the downstream sediment transport. We used a sediment cascade model and a stochastic weather generator to study the detectability under a range of conditions such as different sediment sampling durations and different mean erosion rates in a debris-flow catchment in the Swiss Alps (Illgraben). We show that sediment yields estimated from short duration records are highly uncertain and that transient sediment supply introduces long-term memory effects. Consequently, climate change impact assessments based on short duration records may be grossly inaccurate, and should be extended with uncertainty estimation.

1 Introduction

The study of erosion rates is fundamental for understanding landscape response to environmental signals such as climate change (e.g., Molnar & England, 1990; Bookhagen & Strecker, 2012; Adams et al., 2020), land use change (e.g., Borrelli et al., 2017), deciphering sedimentary records (e.g., Castelltort & Van Den Driessche, 2003), and for predicting hazards and risk connected to sediment transport processes (Jakob et al., 2005) or riverine ecological habitat (Evans et al., 2006). Spatially averaged erosion rates are usually defined for a given area and at different timescales. Short-term erosion rates can be inferred from measured sediment loads with a representative timescale of years to decades (e.g., Fuller et al., 2003). Long-term estimates, averaged over $\sim 10^5$-years, are commonly inferred from sediment tracing, e.g., by cosmogenic radionuclide concentrations such as ^{10}Be in alluvial sediments (Brown et al., 1995). Comparing such short- and long-term sediment yield estimates has revealed some discrepancies depending on basin size and the dominant erosional process (see Covault et al., 2013, and references therein). Short records are often missing erosional pulses resulting from rare events such as large landslides or extreme rainfall (Kirchner et al., 2001; Schaller et al., 2001; Tomkins et al., 2007). This leads to the underestimation in sediment yields especially in small, natural basins with little opportunity for sediment storage, while larger basins buffer these pulses in floodplains (Wittmann et al., 2011). The variable timescales of sediment production and transfer therefore present significant challenges for observation and prediction.

Observational and modelling challenges in geomorphic systems also arise from nonlinearities due to the complex relationships between climatic forcing, hydrological and sediment connectivity, the biosphere and the different geomorphic thresholds involved in sediment production, storage and transport (e.g., Phillips, 2003; Lancaster & Casebeer, 2007; Van De Wiel & Coulthard, 2010; Coulthard & Van De Wiel, 2013; Pelletier et al., 2015). Recent work highlights the importance of the frequency and magnitude of forcing variables compared to system response timescales (Jerolmack & Paola, 2010) and the signal preservation in the stratigraphic records by undisturbed deposition in short intervals between erosion events (Sadler & Jerolmack, 2015; Paola et al., 2018; Ganti et al., 2020). These perspectives are drawn from observations, theoretical constructs and simple models, e.g., the sandpile model (Bak et al., 1987), and they illustrate the potential impact of the timing of sediment supply and export on basin sediment yields. More complex numerical models are increasingly used to study the non-linear response of sediment flux to variability in forcings (e.g., Tucker & Bras, 2000; Van De Wiel & Coulthard, 2010; Coulthard & Van De Wiel, 2013; Godard & Tucker, 2021). The effect of mass movements and their impact on sediment fluxes on shorter timescales has received less attention. Yet modelling tools are most appropriate to capture the cause-and-effect relations in geomorphic systems, necessary for climate change impact and hazard assessments, and for designing sampling strategies and hazard mitigation structures.

Herein we focus on steep headwater catchments, which are often characterized by mass-wasting processes such as landslides and debris flows (e.g Dietrich & Dunne, 1978; Bennett et al., 2013), fed to the channel in a stochastic manner (Benda & Dunne, 1997a, 1997b), and affecting the downstream sediment flux (Hovius et al., 1997). We use a stochastic process-informed geomorphic modelling perspective to show how (a) sediment supply limitations cause bias and uncertainty in sediment yield estimates; (b) short records affect debris-flow magnitude-frequency distributions; (c) memory effects in sediment yields contrasts in supply-limited and transport-limited systems; and (d) the exact timing and magnitudes of sediment inputs are shredded in the sediment yield.

2 Experimental setup

2.1 Geomorphic System and Climate Forcing Models

We coupled the SedCas sediment cascade model (Bennett et al., 2014) and the AWE-GEN stochastic weather generator (Fatichi et al., 2011) to simulate hydrological and sediment fluxes at the highly active Illgraben debris-flow torrent (4.8 km^2), located in the Swiss Rhône Valley and producing ∼5 debris flows yearly on average (Hirschberg, Badoux, et al., 2021). This model setup was calibrated by (Hirschberg, Fatichi, et al., 2021) against observed climate and debris-flow magnitudes to assess climate change impacts on sediment yield and debris-flow activity in the 21st century and also provided a detailed description of the calibration, validation and sensitivity analysis of the entire model chain (see the article supplement). Here, we ran simulations at high temporal resolution (hourly) while spanning geomorphologically relevant timescales (10k years) and a range of climatic and sediment supply conditions.

SedCas is a conceptual geomorphic system model where the sediment production rates by hillslope landslides (triggered by frost-weathering, rainfall, or randomly) are stochastic and drawn from a prescribed probability distribution (Bennett et al., 2012). These landslides provide sediment to the channel and can be re-mobilized and transported out of the catchment by debris flows and fluvial processes, which are simulated with a conceptual hydrological model.

AWE-GEN is used for the stochastic climatic forcing of SedCas. It produces hourly time series of correlated weather variables (e.g., precipitation, air temperature) at the point scale (Fatichi et al., 2011). It was calibrated against 30 years of observations from a weather station in the vicinity (11 km) of the catchment.

Coupling these models reflects the observation that climate and landslides (sediment input) are stochastic forcings in geomorphic systems (Benda & Dunne, 1997a, 1997b) and that the resulting debris-flow activity (sediment output) depends not only on the recurrence interval of climatic thresholds triggering debris flows, but also on the sediment recharge to the channel (Bovis & Jakob, 1999; Jakob et al., 2005). In the 10k-year simulations, the model parameters remain unchanged and the forcings from climate and sediment recharge are therefore stationary. Hence, the estimated mean sediment yields from the full simulations represent the equilibrium state. The estimated uncertainties result from temporal variability in climate and sediment input, and geomorphic thresholds.

2.2 Modelled Scenarios

We ran SedCas with six scenario setups, as summarized in Table S1. The calibrated setup with frost-weathering as the main hillslope sediment supply mechanism (Bennett et al., 2013) and 25 yearly sediment recharge events on average served as a reference (referred to thermal_ls25 hereafter). To study the effect of the timing (seasonality) of sediment recharge, and decouple it from air temperature, we ran simulations with the same number of hillslope landslides triggered by rainfall and randomly (rainfall_ls25 and random_ls25). For simulating sediment supply-limited conditions we assumed that the probability distribution of landslide magnitudes remains fixed, but we reduced the number of yearly generated landslides from 25 to 16 and 8 with the frost-weathering mechanism (thermal_lS26 and thermal_ls8). This resulted in decreased erosion rates by 1/3 and 2/3, respectively. We additionally considered a transport-limited scenario to quantify signals in the sediment yield introduced by interannual climate variability alone.

All scenario runs were forced with the same 10k-year hourly climate simulated with AWE-GEN and therefore the hydrological variables (e.g., snowcover, soil moisture, discharge, etc.) are identical among the scenarios. When the condition for a hillslope landslide was met, the magnitude was sampled from the same distribution in every scenario (Figure 1a). However, depending on the scenario the number of landslides can differ. To enforce 25, 16 and 8 landslides on average per year, the temperature threshold for the onset of frost-weathering was adjusted (Table S1). The simulated channel sediment storage develops in cycles of transport-limited and supply-limited conditions (Figure 1b) and confirms that the long-term sediment delivery ratio goes to 1 (i.e. no long-term storage). The differences in sediment supply result in distinct distributions of annual sediment yields. The more supply-limited, the more right-skewed is the sediment yield distribution and the lower the mean (Figure 1c).

2.3 Analysis of Long-Term Simulations

Each scenario simulation (Table S1) was resampled with different sampling durations to quantify uncertainties in annual sediment yields and their interannual variability. The full time series was split into periods from 1 to 100 years, and the mean and variance of the sediment yield were estimated for each subset. The uncertainties in these estimates were computed to analyze (a) the effects of short records on the sediment output and (b) the detectability of differences in sediment input between the scenarios.

Sediment storage is a source of non-linearity in geomorphic systems (Phillips, 2003). To identify and quantify the long-term memory effects in sediment yields induced by temporary sediment storage, we analyzed long-term correlation in sediment yields using detrended fluctuation analysis (DFA, Peng et al., 1994) using Python (Rydin & Hassan, 2021). DFA is a technique to identify scaling properties in fluctuating or non-stationary time series, e.g., precipitation (Matsoukas et al., 2000) or temperature (e.g., Koscielny-Bunde et al., 1998; Shao & Ditlevsen, 2016). The mean of the detrended variance scales with sampling record duration s as $\overline{F(s)} \propto s^{\alpha}$. Applying DFA on uncorrelated random

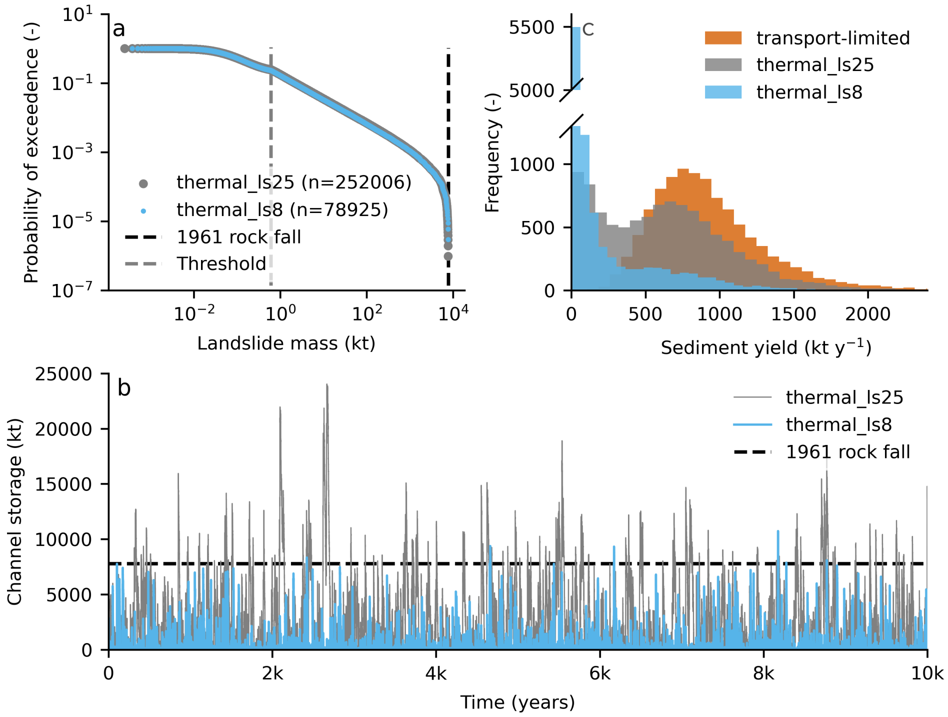

Figure 1. Comparison of different sediment supply scenarios (see Table S1); "thermal_ls25" is the original model setup and calibrated for Illgraben; "transport-limited" and "thermal_ls8" are hypothetical scenarios with unlimited and reduced sediment supply, respectively. (a) Magnitude-frequency distributions of the hillslope landslides generated with SedCas (Bennett et al., 2012). (b) Example time series of the channel sediment storage available for mobilization, with indication of the largest observed rockfall in 1961. (c) Histograms of simulated annual sediment yields.

series (white noise) results in $\alpha = 0.5$ (Kantelhardt et al., 2002). Time series with long-term memory manifest in $\alpha > 0.5$ (Figure S2a). When plotting α as a function of s, i.e. the local slope from the $s - \overline{F(s)}$ plots, the representative timescales and scaling properties can be identified visually (Figure S1 Bryce & Sprague, 2012). We also examined the presence of long-term memory by fitting an ARFIMA model to the sediment yield time series and estimated the differencing order d which is related to the Hurst exponent H as $d = H - 0.5$, where $d > 0$ ($H > 0.5$) is also indicative of long-term memory (Montanari et al., 1997).

3 Results

3.1 Effects of Short Records on Sediment Yield Estimates

Analyses are presented for annual sediment yields and corresponds to the mean mass of sediment exported from the catchment by debris flows per year (unless declared differently). The estimated mean annual sediment yield $\hat{\mu}$ can be both greatly over- or underestimated in all scenarios if based on short records (Figure 2a). The uncertainty is largest for thermal_ls25, where $\hat{\mu}$ can be biased by a factor of $\sim$2 even after 30 years of measurements. Although uncertainty bounds of $\hat{\mu}$ for different scenarios may overlap even after 50 years, there are distinct equilibria. Thus, sediment-supply regime changes are likely to be identified after 30 years of sampling in this system. Underestimating $\hat{\mu}$ based on short records is most likely for the strongly supply limited thermal_ls8.

The rate at which the uncertainty in $\hat{\mu}$ drops is related to the effect of record duration, interannual variance, and interannual memory on the standard error of $\hat{\mu}$ (Montgomery & Runger, 2018). Similarly to $\hat{\mu}$, the estimate of the interannual variance (standard deviation) of annual sediment yields $\hat{\sigma}$ is affected by record duration, but with more overlap between the scenarios (Figure 2b). However, $\hat{\sigma}$ is underestimated in all scenarios for short records, and this effect is stronger for supply-limited scenarios. As a consequence, in order to not underestimate $\hat{\sigma}$, observations of ∼30 years are necessary especially for supply-limited conditions. Repeating the same analysis for the annual total sediment yield (including fluvial transport) and the annual number of debris flows resulted in the same patterns (Figures S2, S4).

The scenarios with the same number of landslides as thermal_ls25 but different triggering mechanisms showed very similar results (Figures 2c, S2). These scenarios differ in the seasonality of sediment recharge, but such high-frequency variations were not distinctly transmitted to the outlet, and therefore invisible in the annual sediment yields. Comparing the thermal scenarios ls_8, ls_16 and ls_25 shows a clear effect of reduced sediment supply in diminishing mean sediment yields and increasing interannual variability. Although the climate forcing remained the same among the scenarios, by altering sediment supply, the coefficient of variation (CV) increased from 0.7 in the transport-limited case, to ∼1 for the ls25 scenarios and to 1.5 and 2.3 for the more supply-limited scenarios (Figure 2c).

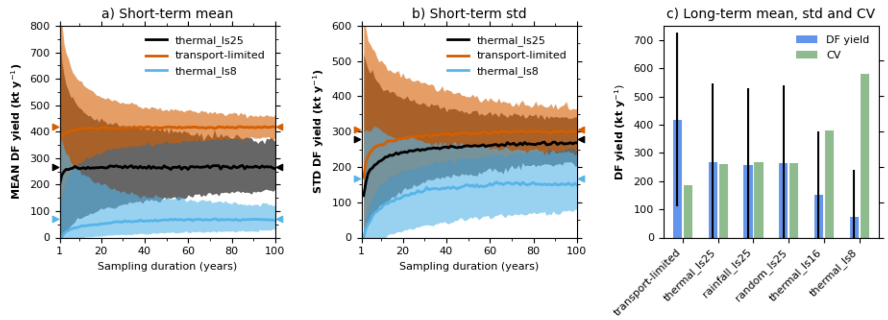

Figure 2. Sensitivity to record duration for (a) mean and (b) standard deviation of annual sediment yields for three scenarios. The medians (solid line) and the 5th-95th percentile range (shaded area) were computed by resampling the 10k-year simulations. Triangles mark the long-term values. (c) The sediment yields long-term mean ± 1 standard deviation (black lines) and coefficient of variation (CV) for all considered scenarios.

3.2 Observed and Simulated Debris-Flow Magnitude-Frequency Distributions

Magnitude-frequency (MF) distributions were estimated for simulated debris-flow events for all scenarios and compared with observations for the same record duration of 18 years (Figure 3). The distributions are characterized by a power-law tail and range from $8{\cdot}10^3$ to $7{\cdot}10^5$ m^3. The observations lie within the simulated uncertainties of the transport-limited, thermal_ls25 and thermal_ls8 scenarios. The simulated magnitudes tend to overestimate observations and this is attributed to the temporal rainfall structure generated with AWE-GEN and the streamflow that results in these extreme events (Hirschberg, Fatichi, et al., 2021). The power-law tails of the different sediment supply scenarios look similar, although the actual number of debris-flow events may vary from less than one to more than four per year (Figure S4). It seems impossible to discern the sediment production process from the MF distributions of debris-flow events (Bennett et al., 2014). However, the magnitudes of the very largest events are significantly different between the scenarios and point to the fact that the observations are more likely to result from the supply-limited scenarios (red histograms in Figure 3). The observations, based on 18 years of continuous monitoring, seem to be cutoff at $8{\cdot}10^4$ m^3. However, volume estimates of destructive debris flows in 1961 suggest the possibility of larger events in the order of $\sim 5{\cdot}10^5$ m^3 (Hürlimann et al., 2003), which are mostly absent in short records.

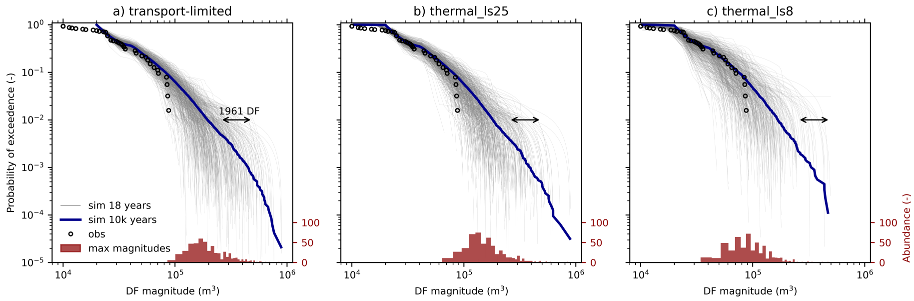

Figure 3. Debris-flow magnitude-frequency distributions. The blue lines were estimated from the 10k-year simulations. The grey lines are fits to 18-year-long subsets of the simulations, which corresponds to the time period of the observations (black circles). The histograms show the largest debris-flow magnitudes (95th percentile) from the simulation subset. The range of volume estimates from large destructive debris flows in 1961 are indicated by the black arrows.

3.3 Long-Term Memory Effects in Sediment Fluxes

A key premise in this work is that sediment supply limitations may lead to long-term memory effects in sediment yields. In the DFA, all scenarios show the typical power-law scaling of the $s{-}\overline{F(s)}$ relation (Figure S5). The scaling behavior, expressed as the exponent α, was more pronounced for short records (Figure 4). This bias for short records is expected and has no physical meaning (Peng et al., 1994). The presence of long-term memory is evident in the simulations with stable slopes around $\alpha{\approx}0.75$ between $\sim$8-50 years for the ls25 scenarios (Figure 4a,d,e). The scenarios with decreased sediment supply (thermal_lS26, thermal_ls8) had a shorter period of stable slope ($\sim$8-20 years), but the higher slopes ($\alpha > 0.75$) indicate stronger long-term memory at these timescales (Figure 4b,c). Depending on the scenario, α scattered more after 20-50 years and trended towards 0.5, indicating weakening memory and random signals at longer timescales. The transport-limited scenario differs from all the others because α stabilizes at 0.5 already for small s. Hence, there are no long-term memory effects in the sediment output induced by climate, which only imprints a short-term memory signal on sediment yields.

Long-term memory is also evident from the uncertainty in $\hat{\mu}$ (Figure 2a). The drop in uncertainty is inversely related to s for the transport-limited case, while the drop for the other scenarios is much slower. A similar decrease in the uncertainty for those scenarios could only be reproduced by fitting an ARFIMA time series with long-term memory $H{>}0.5$ (Figure S6). Together with the findings of the DFA analysis, this confirms that the long-term memory in the other scenarios was induced by different sediment supply regimes.

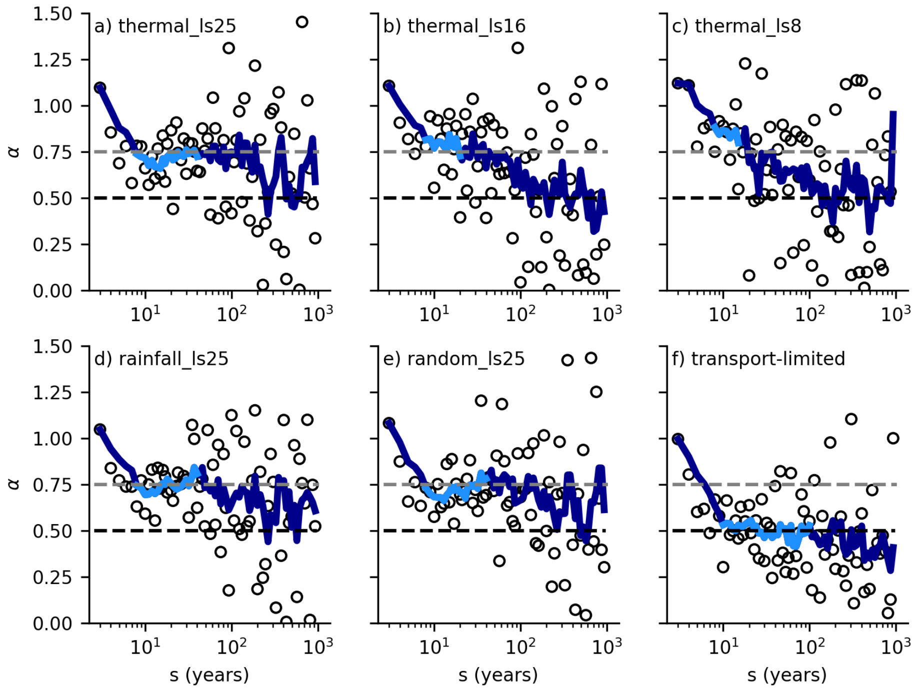

Figure 4. Local slope (exponent α) of the $s - \overline{F(s)}$ relation in sediment yields shown in Figure S5 as a function of sampling duration s. The dots represent the slope between two individual points and the dark blue line is the moving average from five points. The light blue lines mark the timescales with approximately stable slopes (see text). The black dashed line at α=0.5 shows the condition of no long-term correlation. The dashed grey line at α=0.75 serves for comparison with strong long-term memory being present.

4 Discussion

4.1 Short-Long-Term Discrepancy in Sediment Yield Estimates

We quantified the timescales and amplitude ranges of variabilities in sediment fluxes in Illgraben. We investigated the influence of several different sediment supply scenarios and sampling timescales on sediment yields. Short records (<20 years) resulted in uncertainty in mean ($\hat{\mu}$) and standard deviation ($\hat{\sigma}$) of annual sediment yield of a factor of 2. With current erosion rates, the likelihood of over- or underestimation of $\hat{\mu}$ was balanced. However, in scenarios resulting in more supply-limited conditions, $\hat{\mu}$ was likely to be underestimated if based on short records. The interannual variability $\hat{\sigma}$ was underestimated in all scenarios for short records. This is an inherent effect of undersampling and known from statistics, but compounded by the fact that for supply-limited scenarios, the long-term memory was stronger (Figure 4). If the sediment supply was further decreased, the sediment yield would converge to zero and lose the long-term memory effect. Therefore, interannual variability is expected to be underestimated in short records and geomorphic systems with memory.

Discrepancies between short- and long-term estimates of sediment yield has been attributed to low-frequency high-magnitude pulses of erosion (e.g., Kirchner et al., 2001; Tomkins et al., 2007). Here, we are able to identify what this process is. If it was caused by low-frequency high-magnitude rainfall events leading to large debris flows, the discrepancy would be visible in all scenarios because all scenarios were forced with the same climate. This points to the role of the stochasticity in hillslope landsliding, which induced stronger long-term memory for supply-limited scenarios (Figure 4). The discrepancy in short- and long-term $\hat{\mu}$ in this study was therefore driven by the sequencing of random large sediment supply events. We acknowledge that our spatially-lumped model neglects variability in space and is therefore not ideal to study the impact of single extreme rainfall events, because the hydrological connectivity may be an important limiting factor for sediment flux even in small basins (Reid et al., 2007). Nevertheless, the simulated dynamics reflect observations of elevated debris-flow activity or sediment yield after large sediment supply events in Illgraben and other basins after landslides (Hürlimann et al., 2003), earthquakes (e.g., Tang et al., 2011), or wild fires (Cannon et al., 2001), and can lead to elevated sediment yields even at the 10^3-year timescale (Korup, 2012).

4.2 Implications for Risk Assessment and Mitigation

Our findings point to challenges in assessment of climate change impacts on sediment flux, hazard and design of engineering structures (e.g., sediment retention basins), which are based on short records of sediment yields. Many sediment transport and debris-flow observation records are short and our simulations have shown the implied risks related to uncertainties in sediment yields (Figure 2) and underestimating the possibility of large debris flows (Figure 3). In basins with short records, additional methods and secondary observations providing information for longer timescales should be consulted. In debris-flow hazard assessments, events have been reconstructed using dating techniques such as dendrochronology (e.g., Stoffel et al., 2008) or radiocarbon dating (e.g., Jakob et al., 2017) to establish MF relationships. Because these methods are time and cost intensive, effort has been put into extrapolating existing MF curves at the regional scale in relation to morphometric catchment characteristics (de Haas & Densmore, 2019), fan area, or fan volume (Jakob et al., 2020). In addition to these procedures, stochastic modelling frameworks, as presented here, are helpful for quantifying uncertainties related to climatic forcing and transient sediment supply and to extend MF distributions beyond short-term observations (Figure 3).

4.3 Preservation of Climate Signals in Sediment Records

The sediment supply mechanism (thermal, rainfall or random) in our system had no effect on the long-term sediment yield estimates. These mechanisms mainly differ in their timing and seasonality. For example, frost-weathering is most active in cold months while intense rainfall mainly occurs in warm months. Because the frequency and magnitude of these processes are similar, their differences were not apparent in the sediment output, and their signals were shredded (Jerolmack & Paola, 2010).

Finally, it has been argued that environmental signals will only be recorded and identified in sediment transport measurements or the sedimentary record if their timescale exceeds the response time of the system (Castelltort & Van Den Driessche, 2003; Hoffmann, 2015), unless the magnitude of the signal exceeds the natural variability (Jerolmack & Paola, 2010). For Illgraben and similar basins this means that a change needs to persist for only >30 years. This may seem short, but when considering that this catchment's erosion rate exceeds other Alpine sites by about one order of magnitude (Stutenbecker et al., 2018; Delunel et al., 2020) and has relatively little opportunity to store sediments (i.e. only temporary storage), this timescale can be expected to be much larger where storage opportunities exist and where other controls dominate, such as glacial periods (e.g., Hoffmann, 2015; Ganti et al., 2016). Stochastic frameworks as presented here are helpful in quantifying the role of different forcings and future research should aim at quantifying it for other basins with other sediment supply regimes and other geomorphic system models.

5 Conclusions

We quantified the uncertainties introduced by climate forcing, transient sediment supply and sampling record duration on estimates of sediment yields in Illgraben by simulating 10k years with a sediment cascade model forced by hourly stochastic weather. Consistent with field observations from other basins, estimates of mean annual sediment yield may be underestimated when based on short records and this effect becomes stronger when the sediment supply is decreased. This results from transient sediment supply by hillslope landslides leading to cycles of transport- and supply-limited conditions. We showed that such cycles cause long-term memory in sediment output at timescales of up to $\sim$50 years. Consequently, the interannual variability of sediment yield estimates was underestimated if sediment supply was limited. Furthermore, we showed that the signal from changing sediment supply mechanisms (triggering conditions), which affect the timing and seasonality of sediment recharge, was shredded. Climate change impacts on sediment supply may therefore only be recorded in the sediment output if they considerably alter the erosion rate of the geomorphic system. The results highlight the importance of characterizing sediment supply events with regard to their stochastic nature. This will support decision making and decrease the risk of misinterpretation both in natural hazard and climate change impact assessments, especially if they are based on short records.

Acknowledgments

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References

Adams, B. A., Whipple, K. X., Forte, A. M., Heimsath, A. M., & Hodges, K. V. (2020). Climate controls on erosion in tectonically active landscapes. *Science Advances*, *6*(42). doi: 10.1126/sciadv.aaz3166

Bak, P., Tang, C., & Wiesenfeld, K. (1987, jul). Self-organized criticality: An explanation of the 1/<i>f</i> noise. *Physical Review Letters*, *59*(4), 381. Retrieved from `https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.59.381` doi: 10.1103/PhysRevLett.59.381

Benda, L., & Dunne, T. (1997a). Stochastic forcing of sediment routing and storage in channel networks. *Water Resources Research*, *33*(12), 2865–2880. doi: 10.1029/97WR02387

Benda, L., & Dunne, T. (1997b). Stochastic forcing of sediment supply to channel networks from landsliding and debris flow. *Water Resources Research*, *33*(12), 2849–2863. doi: 10.1029/97WR02388

Bennett, G. L., Molnar, P., Eisenbeiss, H., & Mcardell, B. W. (2012). Erosional power in the Swiss Alps: Characterization of slope failure in the Illgraben. *Earth Surface Processes and Landforms*, *37*(15), 1627–1640. doi: 10.1002/esp.3263

Bennett, G. L., Molnar, P., McArdell, B. W., & Burlando, P. (2014). A probabilistic sediment cascade model of sediment transfer in the Illgraben. *Water Resources Research*, *50*(2), 1225–1244. doi: 10.1002/2013WR013806

Bennett, G. L., Molnar, P., McArdell, B. W., Schlunegger, F., & Burlando, P. (2013). Patterns and controls of sediment production, transfer and yield in the Illgraben. *Geomorphology*, *188*, 68–82. Retrieved from `http://dx.doi.org/10.1016/j.geomorph.2012.11.029` doi: 10.1016/j.geomorph.2012.11.029

Bookhagen, B., & Strecker, M. R. (2012, apr). Spatiotemporal trends in erosion rates across a pronounced rainfall gradient: Examples from the southern Central Andes. *Earth and Planetary Science Letters*, *327-328*, 97–110. doi: 10.1016/J.EPSL.2012.02.005

Borrelli, P., Robinson, D. A., Fleischer, L. R., Lugato, E., Ballabio, C., Alewell, C., ... Panagos, P. (2017). An assessment of the global impact of 21st century land use change on soil erosion. *Nature Communications*, *8*(1). Retrieved from `www.nature.com/naturecommunications` doi: 10.1038/s41467-017-02142-7

Bovis, M. J., & Jakob, M. (1999). The role of debris supply conditions in predicting debris flow activity. *Earth Surface Processes and Landforms*, *24*(11), 1039–1054. doi: 10.1002/(SICI)1096-9837(199910)24:11⟨1039::AID-ESP29⟩3.0.CO;2-U

Brown, E. T., Stallard, R. F., Larsen, M. C., Raisbeck, G. M., & Yiou, F. (1995). Denudation rates determined from the accumulation of in situ-produced 10Be in the luquillo experimental forest, Puerto Rico. *Earth and Planetary Science Letters*, *129*(1-4), 193–202. doi: 10.1016/0012-821X(94)00249-X

Bryce, R. M., & Sprague, K. B. (2012). Revisiting detrended fluctuation analysis. *Scientific Reports*, *2*. doi: 10.1038/srep00315

Cannon, S. H., Kirkham, R. M., & Parise, M. (2001, aug). Wildfire-related debris-flow initiation processes, Storm King Mountain, Colorado. *Geomorphology*, *39*(3-4), 171–188. doi: 10.1016/S0169-555X(00)00108-2

Castelltort, S., & Van Den Driessche, J. (2003). How plausible are high-frequency sediment supply-driven cycles in the stratigraphic record? *Sedimentary Geology*, *157*(1-2), 3–13. doi: 10.1016/S0037-0738(03)00066-6

Coulthard, T. J., & Van De Wiel, M. J. (2013). Climate, tectonics or morphology: What signals can we see in drainage basin sediment yields? *Earth Surface Dynamics*, *1*(1), 13–27. doi: 10.5194/esurf-1-13-2013

Covault, J. A., Craddock, W. H., Romans, B. W., Fildani, A., & Gosai, M. (2013). Spatial and temporal variations in landscape evolution: Historic and longer-term sediment flux through global catchments. *Journal of Geology*, *121*(1), 35–56. doi: 10.1086/668680

de Haas, T., & Densmore, A. L. (2019). Debris-flow volume quantile prediction from catchment morphometry. *Geology*, *47*(8), 1–4. Retrieved from `https://pubs.geoscienceworld.org/gsa/geology/article/571535/Debrisflow-volume-quantile-prediction-from` doi: 10.1130/G45950.1

Delunel, R., Schlunegger, F., Valla, P. G., Dixon, J., Glotzbach, C., Hippe, K., ... Christl, M. (2020, dec). Late-Pleistocene catchment-wide denudation patterns across the European Alps. *Earth-Science Reviews*, *211*, 103407. Retrieved from `https://doi.org/10.1016/j.earscirev.2020.103407` doi: 10.1016/j.earscirev.2020.103407

Dietrich, W. E., & Dunne, T. (1978). Sediment budget for a small catchment in mountainous terrain. *Zeitschrift für Geomorphologie*, *29*, 191–206. Retrieved from `https://www.researchgate.net/publication/247467187` doi: 10.1130/0091-7613(2001)029

Evans, D. J., Gibson, C. E., & Rossell, R. S. (2006, sep). Sediment loads and sources in heavily modified Irish catchments: A move towards informed management strategies. *Geomorphology*, *79*(1-2), 93–113. doi: 10.1016/j.geomorph.2005.09.018

Fatichi, S., Ivanov, V. Y., & Caporali, E. (2011). Simulation of future climate scenarios with a weather generator. *Advances in Water Resources*, *34*(4), 448–467. Retrieved from `http://dx.doi.org/10.1016/j.advwatres.2010.12.013` doi: 10.1016/j.advwatres.2010.12.013

Fuller, C. W., Willett, S. D., Hovius, N., & Slingerland, R. (2003). Erosion Rates for Taiwan Mountain Basins: New Determinations from Suspended Sediment Records and a Stochastic Model of Their Temporal Variation. *The Journal of Geology*, *111*(1), 71–87. doi: 10.1086/344665

Ganti, V., Hajek, E. A., Leary, K., Straub, K. M., & Paola, C. (2020). Morphodynamic Hierarchy and the Fabric of the Sedimentary Record. *Geophysical Research Letters*, *47*(14). Retrieved from `https://doi.org/` doi: 10.1029/

2020GL087921

Ganti, V., Von Hagke, C., Scherler, D., Lamb, M. P., Fischer, W. W., & Avouac, J. P. (2016). Time scale bias in erosion rates of glaciated landscapes. *Science Advances*, *2*(10). Retrieved from `http://advances.sciencemag.org/` doi: 10.1126/sciadv.1600204

Godard, V., & Tucker, G. E. (2021, sep). Influence of Climate-Forcing Frequency on Hillslope Response. *Geophysical Research Letters*, *48*(18), e2021GL094305. Retrieved from `https://onlinelibrary.wiley.com/doi/full/10.1029/2021GL094305https://onlinelibrary.wiley.com/doi/abs/10.1029/2021GL094305https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021GL094305` doi: 10.1029/2021GL094305

Hirschberg, J., Badoux, A., McArdell, B. W., Leonarduzzi, E., & Molnar, P. (2021). Evaluating methods for debris-flow prediction based on rainfall in an Alpine catchment. *Natural Hazards and Earth System Sciences*, *21*(9), 2773–2789. doi: 10.5194/nhess-21-2773-2021

Hirschberg, J., Fatichi, S., Bennett, G. L., McArdell, B. W., Peleg, N., Lane, S. N., ... Molnar, P. (2021). Climate Change Impacts on Sediment Yield and Debris-Flow Activity in an Alpine Catchment. *Journal of Geophysical Research: Earth Surface*, *126*(1). doi: 10.1029/2020JF005739

Hoffmann, T. (2015). Sediment residence time and connectivity in non-equilibrium and transient geomorphic systems. *Earth-Science Reviews*, *150*, 609–627. Retrieved from `http://dx.doi.org/10.1016/j.earscirev.2015.07.008` doi: 10.1016/j.earscirev.2015.07.008

Hovius, N., Stark, C. P., & Allen, P. A. (1997). Sediment flux from a mountain belt derived by landslide mapping. *Geology*, *25*(3), 231–234. doi: 10.1130/0091-7613(1997)025⟨0231:SFFAMB⟩2.3.CO;2

Hürlimann, M., Rickenmann, D., & Graf, C. (2003). Field and monitoring data of debris-flow events in the Swiss Alps. *Canadian Geotechnical Journal*, *40*(1), 161–175. doi: 10.1139/t02-087

Jakob, M., Bovis, M., & Oden, M. (2005). The significance of channel recharge rates for estimating debris-flow magnitude and frequency. *Earth Surface Processes and Landforms*, *30*(6), 755–766. doi: 10.1002/esp.1188

Jakob, M., Mark, E., McDougall, S., Friele, P., Lau, C. A., & Bale, S. (2020). Regional debris-flow and debris-flood frequency–magnitude relationships. *Earth Surface Processes and Landforms*. doi: 10.1002/esp.4942

Jakob, M., Weatherly, H., Bale, S., Perkins, A., & MacDonald, B. (2017). A Multi-Faceted Debris-Flood Hazard Assessment for Cougar Creek, Alberta, Canada. *Hydrology*, *4*(1), 7. doi: 10.3390/hydrology4010007

Jerolmack, D. J., & Paola, C. (2010). Shredding of environmental signals by sediment transport. *Geophysical Research Letters*, *37*(19), 1–5. doi: 10.1029/2010GL044638

Kantelhardt, J. W., Zschiegner, S. A., Koscielny-Bunde, E., Havlin, S., Bunde, A., & Stanley, H. E. (2002). Multifractal detrended fluctuation analysis of nonstationary time series. *Physica A: Statistical Mechanics and its Applications*, *316*(1-4), 87–114. doi: 10.1016/S0378-4371(02)01383-3

Kirchner, J. W., Finkel, R. C., Riebe, C. S., Granger, D. E., Clayton, J. L., King, J. G., & Megahan, W. F. (2001). Mountain erosion over 10 yr, 10 k.y., and 10 m.y. time scales. *Geology*, *29*(7), 591–594. doi: 10.1130/0091-7613(2001)029⟨0591

Korup, O. (2012, may). *Earth's portfolio of extreme sediment transport events* (Vol. 112) (No. 3-4). Elsevier. doi: 10.1016/j.earscirev.2012.02.006

Koscielny-Bunde, E., Bunde, A., Havlin, S., Roman, H. E., Goldreich, Y., & Schellnhuber, H. J. (1998). Indication of a universal persistence law governing atmospheric variability. *Physical Review Letters*, *81*(3), 729–732. doi: 10.1103/PhysRevLett.81.729

Lancaster, S. T., & Casebeer, N. E. (2007). Sediment storage and evacuation in headwater valleys at the transition between debris-flow and fluvial processes. *Geology*, *35*(11), 1027–1030. doi: 10.1130/G239365A.1

Matsoukas, C., Islam, S., & Rodriguez-Iturbe, I. (2000). Detrended fluctuation analysis of rainfall and streamflow time series. *Journal of Geophysical Research Atmospheres*, *105*(D23), 29,165–29,172. doi: 10.1029/2000JD900419

McArdell, B. W., & Hirschberg, J. (2020). *Debris-flow volumes at the Illgraben 2000-2017.* EnviDat. doi: 10.16904/envidat.173

Molnar, P., & England, P. (1990). Late Cenozoic uplift of mountain ranges and global climate change: Chicken or egg? *Nature*, *346*(6279), 29–34. doi: 10.1038/346029a0

Montanari, A., Rosso, R., & Taqqu, M. S. (1997). Fractionally differenced ARIMA models applied to hydrologic time series: Identification, estimation, and simulation. *Water Resources Research*, *33*(5), 1035–1044. doi: 10.1029/97WR00043

Montgomery, D. C., & Runger, G. C. (2018). *Applied statistics and probability for engineers.* Wiley Hoboken, NJ.

Paola, C., Ganti, V., Mohrig, D., Runkel, A. C., & Straub, K. M. (2018). Time Not Our Time: Physical Controls on the Preservation and Measurement of Geologic Time. *Annual Review of Earth and Planetary Sciences*, *46*, 409–438. Retrieved from `https://doi.org/10.1146/annurev-earth-082517-` doi: 10.1146/annurev-earth-082517-010129

Pelletier, J. D., Brad Murray, A., Pierce, J. L., Bierman, P. R., Breshears, D. D., Crosby, B. T., ... Yager, E. M. (2015). Forecasting the response of Earth's surface to future climatic and land use changes: A review of methods and research needs. *Earth's Future*, *3*(7), 220–251. doi: 10.1002/2014EF000290

Peng, C. K., Buldyrev, S. V., Havlin, S., Simons, M., Stanley, H. E., & Goldberger, A. L. (1994). Mosaic organization of DNA nucleotides. *Physical Review E*, *49*(2), 1685–1689. doi: 10.1103/PhysRevE.49.1685

Phillips, J. D. (2003). Sources of nonlinearity and complexity in geomorphic systems. *Progress in Physical Geography*, *27*(1), 1–23. doi: 10.1191/0309133303pp340ra

Reid, S. C., Lane, S. N., Montgomery, D. R., & Brookes, C. J. (2007). Does hydrological connectivity improve modelling of coarse sediment delivery in upland environments? *Geomorphology*, *90*(3-4), 263–282. doi: 10.1016/j.geomorph.2006.10.023

Rydin, & Hassan, G. (2021, jan). *LRydin/MFDFA: v0.4.* Zenodo. Retrieved from `https://doi.org/10.5281/zenodo.4450762` doi: 10.5281/zenodo.4450762

Sadler, P. M., & Jerolmack, D. J. (2015). Scaling laws for aggradation, denudation and progradation rates: The case for time-scale invariance at sediment sources and sinks. *Geological Society Special Publication*, *404*, 69–88. Retrieved from `http://dx.doi.org/10.1144/SP404.7` doi: 10.1144/SP404.7

Schaller, M., Von Blanckenburg, F., Hovius, N., & Kubik, P. W. (2001, jun). Large-scale erosion rates from in situ-produced cosmogenic nuclides in European river sediments. *Earth and Planetary Science Letters*, *188*(3-4), 441–458. doi: 10.1016/S0012-821X(01)00320-X

Shao, Z. G., & Ditlevsen, P. D. (2016). Contrasting scaling properties of interglacial and glacial climates. *Nature Communications*, *7*, 1–8. doi: 10.1038/ncomms10951

Stoffel, M., Conus, D., Grichting, M. A., Lièvre, I., & Maître, G. (2008). Unraveling the patterns of late Holocene debris-flow activity on a cone in the Swiss Alps: Chronology, environment and implications for the future. *Global and Planetary Change*, *60*(3-4), 222–234. doi: 10.1016/j.gloplacha.2007.03.001

Stutenbecker, L., Delunel, R., Schlunegger, F., Silva, T. A., Šegvić, B., Girardclos, S., ... Christl, M. (2018). Reduced sediment supply in a fast eroding landscape? A multi-proxy sediment budget of the upper Rhône basin, Central Alps. *Sedimentary Geology*, *375*, 105–119. doi: 10.1016/j.sedgeo.2017.12.013

Tang, C., Zhu, J., Ding, J., Cui, X., Chen, L., & Zhang, J. (2011). Catastrophic debris flows triggered by a 14 August 2010 rainfall at the epicenter of the Wenchuan earthquake. *Landslides*, *8*(4), 485–497. doi: 10.1007/s10346-011-0269-5

Tomkins, K. M., Humphreys, G. S., Wilkinson, M. T., Fink, D., Hesse, P. P., Doerr, S. H., … Blake, W. H. (2007). Contemporary versus long-term denudation along a passive plate margin: The role of extreme events. *Earth Surface Processes and Landforms*, *32*(7), 1013–1031. doi: 10.1002/esp.1460

Tucker, G. E., & Bras, R. L. (2000). A stochastic approach to modeling the role of rainfall variability in drainage basin evolution. *Water Resources Research*, *36*(7), 1953–1964. doi: 10.1029/2000WR900065

Van De Wiel, M. J., & Coulthard, T. J. (2010). Self-organized criticality in river basins: Challenging sedimentary records of environmental change. *Geology*, *38*(1), 87–90. doi: 10.1130/G30490.1

Wittmann, H., von Blanckenburg, F., Maurice, L., Guyot, J.-L., Filizola, N., & Kubik, P. W. (2011, may). Sediment production and delivery in the Amazon River basin quantified by in situ–produced cosmogenic nuclides and recent river loads. *GSA Bulletin*, *123*(5-6), 934–950. Retrieved from http://www.geosociety.org/pubs/ doi: 10.1130/B30317.1

Supporting Information for "Sediment Yield and its Interannual Variability are Underestimated in Supply-Limited Mountain Basins with Short Records"

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3. Table S1

Text S1: Sediment Cascade Model (SedCas)

SedCas is a conceptual model based on the geomorphic concept of sediment cascades in headwaters (Bennett et al., 2014; Berger et al., 2011). It consists of two sediment reservoirs on the hillslope and the channel. Larger hillslope failures are triggered either by frost-weathering, rainfall or in random intervals, while smaller failures occur more often and randomly in time. A fraction of these sediments is redeposited on the hillslope and the remainder is directly transferred to the channel by gravity-driven processes. Sediment transfer in the channel and out of the catchment is triggered by surface runoff. To this end, the water balance is solved with a linear reservoir approach for hydrological response units and under consideration of the main hydrological processes (i.e. snow accumulation and melt, runoff generation, evapotranspiration). The channel sediment storage is eroded by sediment-laden floods and debris flows triggered by surface runoff. The total mobilized sediment volume depends on the surface discharge and the channel sediment storage.

The hillslope failures are sampled from a magnitude-frequency distribution characterized by a power-law tail (Bennett et al., 2012). This reflects the observation that the landslides feeding the channel with sediments and the weather conditions initiating sediment flow out of the catchment are stochastic forcings (see also model of Benda & Dunne, 1997a, 1997b). Although this modelling framework does not allow for a detailed investigation of sediment production and transfer processes in a spatially explicit way, it enables the study of compound impacts of climate on sediment production and transfer processes, and how climate signals are reflected in debris flows and sediment yield at the catchment scale (see also Lu et al., 2005).

Here we use the SedCas setup as described in Hirschberg et al. (2021), where we applied it for future predictions on debris flows and sediment yield in the Illgraben. We conducted the calibration and sensitivity analysis in a Monte Carlo framework based on 17 years of climate and debris-flow observations (McArdell & Hirschberg, 2020). SedCas was calibrated primarily to reproduce debris-flow statistics such as frequency, mean and standard deviation of the magnitudes. Further evidence of the satisfying model performance is supported by the successful reproduction of seasonal patterns in sediment production and transfer.

Text S2: Advanced Weather Generator Model (AWE-GEN)

AWE-GEN produces stochastic hourly time series of correlated weather variables (e.g. precipitation, air temperature, incoming shortwave radiation) at the point scale (Fatichi et al., 2011). It is calibrated against observations collected by the Swiss Meteorological Office (MeteoSwiss) between 1981 and 2010 at the Montana weather station, located about 11 km away from the catchment at similar altitude (1423 m a.s.l.). Because climate statistics are aggregated at a range of spatial scales (from hourly to annual) in the calibration, AWE-GEN reproduces extremes as well as inter-annual variability for considered climate variables. For more details on the model and on how it was calibrated for the Illgraben the reader is referred to Fatichi et al. (2011) and Hirschberg et al. (2021).

Typically, 50, 30-year long time series (1500 years in total) are generated to estimate stochastic uncertainty (e.g. Fatichi et al., 2016). To ensure that natural variability is sufficiently considered, we simulate a time series of 10’000 years. It is representative for the observed climate between 1981 and 2010 and used to force SedCas and determine the long-term means in sediment fluxes.

References

Benda, L., & Dunne, T. (1997a). Stochastic forcing of sediment routing and storage in channel networks. *Water Resources Research*, *33*(12), 2865–2880. doi: 10.1029/97WR02387

Benda, L., & Dunne, T. (1997b). Stochastic forcing of sediment supply to channel networks from landsliding and debris flow. *Water Resources Research*, *33*(12), 2849–2863. doi: 10.1029/97WR02388

Bennett, G. L., Molnar, P., Eisenbeiss, H., & Mcardell, B. W. (2012). Erosional power in the Swiss Alps: Characterization of slope failure in the Illgraben. *Earth Surface Processes and Landforms*, *37*(15), 1627–1640. doi: 10.1002/esp.3263

Bennett, G. L., Molnar, P., McArdell, B. W., & Burlando, P. (2014). A probabilistic sediment cascade model of sediment transfer in the Illgraben. *Water Resources Research*, *50*(2), 1225–1244. doi: 10.1002/2013WR013806

Berger, C., McArdell, B. W., & Schlunegger, F. (2011). Sediment transfer patterns at the Illgraben catchment, Switzerland: Implications for the time scales of debris flow activities. *Geomorphology*, *125*(3), 421–432. doi: 10.1016/j.geomorph.2010.10.019

Fatichi, S. (2021). *ARFIMA simulations.* Retrieved from https://www.mathworks.com/matlabcentral/fileexchange/25611-arfima-simulations

Fatichi, S., Ivanov, V. Y., & Caporali, E. (2011). Simulation of future climate scenarios with a weather generator. *Advances in Water Resources*, *34*(4), 448–467. Retrieved from http://dx.doi.org/10.1016/j.advwatres.2010.12.013 doi:

10.1016/j.advwatres.2010.12.013

Fatichi, S., Ivanov, V. Y., Paschalis, A., Peleg, N., Molnar, P., Rimkus, S., . . . Caporali, E. (2016). Uncertainty partition challenges the predictability of vital details of climate change. *Earth's Future*, *4* (5), 240–251. doi: 10.1002/2015EF000336

Hirschberg, J., Fatichi, S., Bennett, G. L., McArdell, B. W., Peleg, N., Lane, S. N., . . . Molnar, P. (2021). Climate Change Impacts on Sediment Yield and Debris-Flow Activity in an Alpine Catchment. *Journal of Geophysical Research: Earth Surface*, *126* (1). doi: 10.1029/2020JF005739

Lu, H., Moran, C. J., & Sivapalan, M. (2005). A theoretical exploration of catchment-scale sediment delivery. *Water Resources Research*, *41* (9), 1–15. doi: 10.1029/2005WR004018

McArdell, B. W., & Hirschberg, J. (2020). *Debris-flow volumes at the Illgraben 2000-2017.* EnviDat. doi: 10.16904/envidat.173

Montanari, A., Rosso, R., & Taqqu, M. S. (1997). Fractionally differenced ARIMA models applied to hydrologic time series: Identification, estimation, and simulation. *Water Resources Research*, *33* (5), 1035–1044. doi: 10.1029/97WR00043

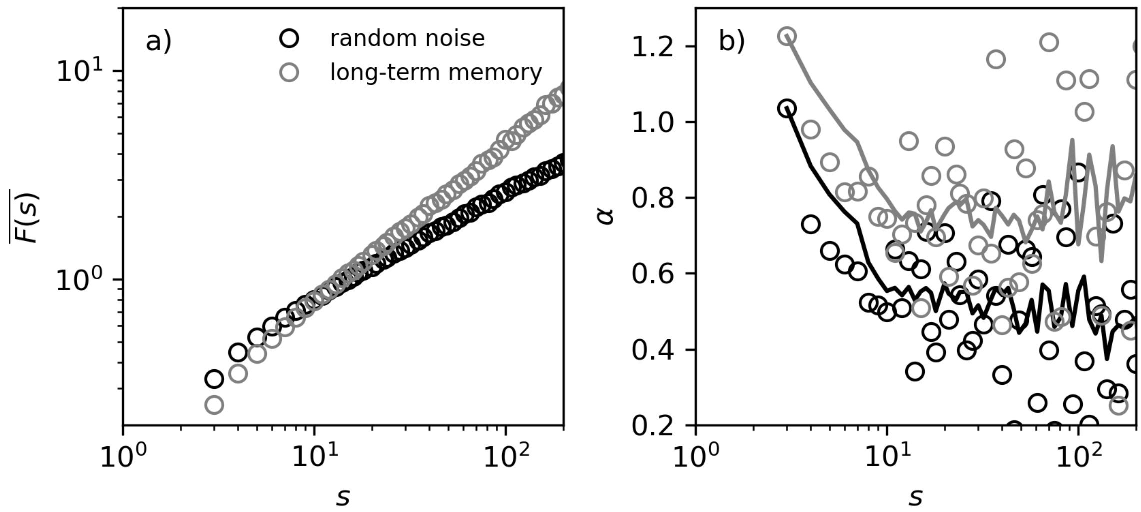

Figure S1. Example DFA analysis using fractional Gaussian noise without (random noise, $\alpha = 0.5$) and with long-term memory ($\alpha = 0.75$). (a) scaling of the mean spread $\overline{F(s)}$ with sampling record length s; (b) local slope (exponent α) computed from the $s - \overline{F(s)}$ pairs.

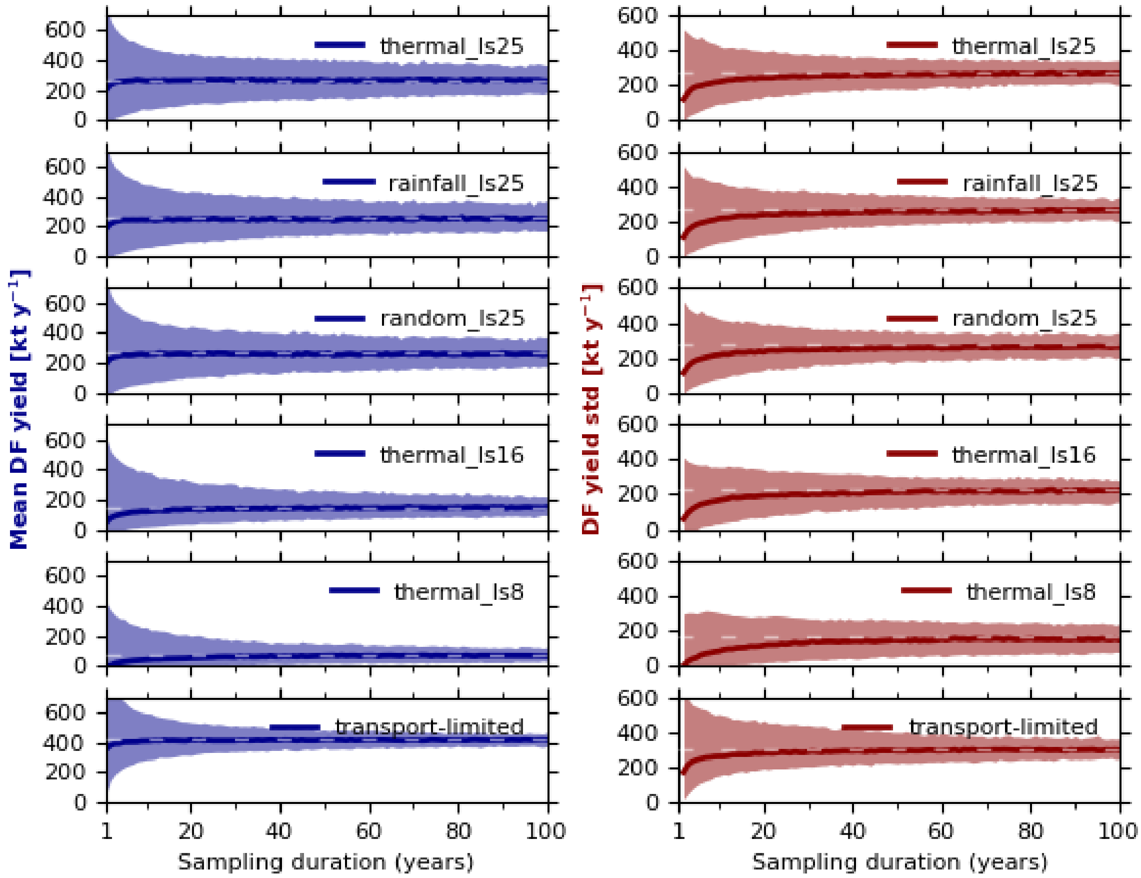

Figure S2. Debris-flow yields for all scenarios as a function of record duration. The median (solid line) and the 5-95 percentile range (shaded area) are shown for all modelled scenarios (Table S1) with SedCas.

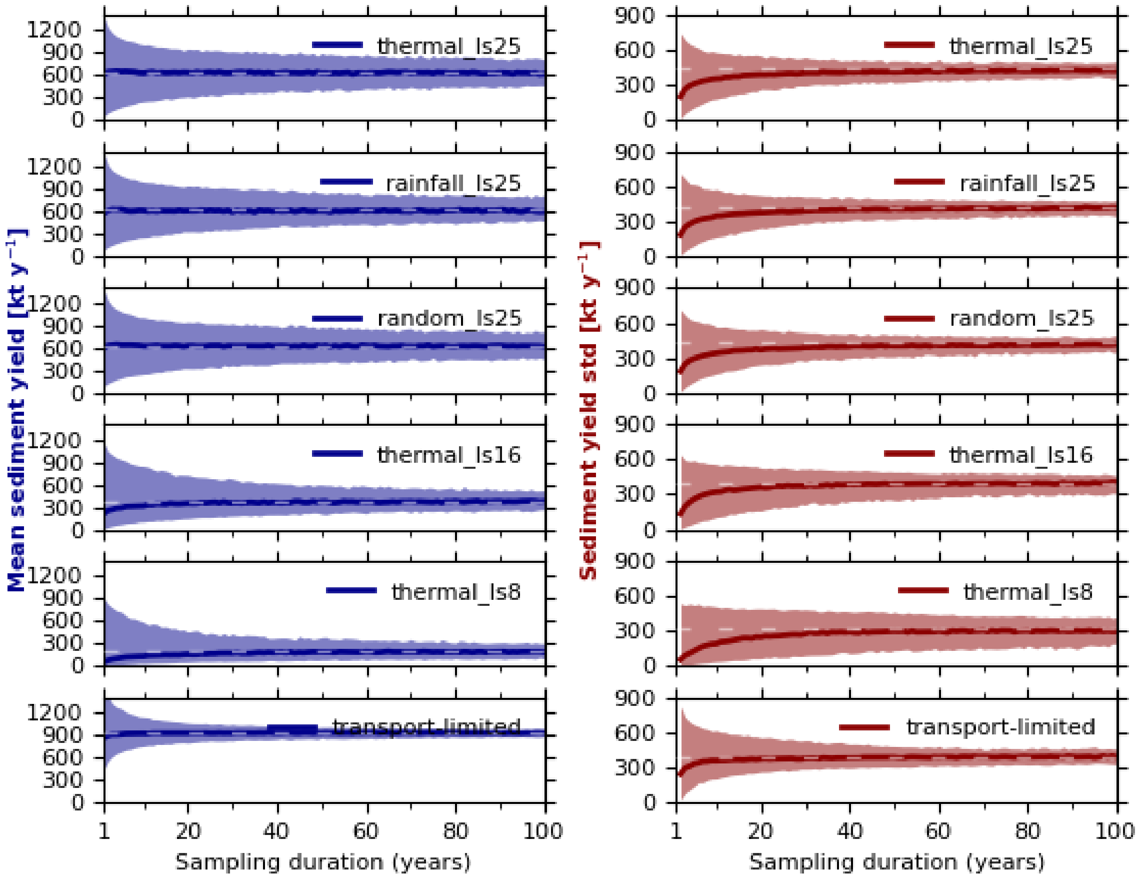

Figure S3. Sediment yields for all scenarios as a function of record duration. The median (solid line) and the 5-95 percentile range (shaded area) are shown for all modelled scenarios (Table S1) with SedCas.

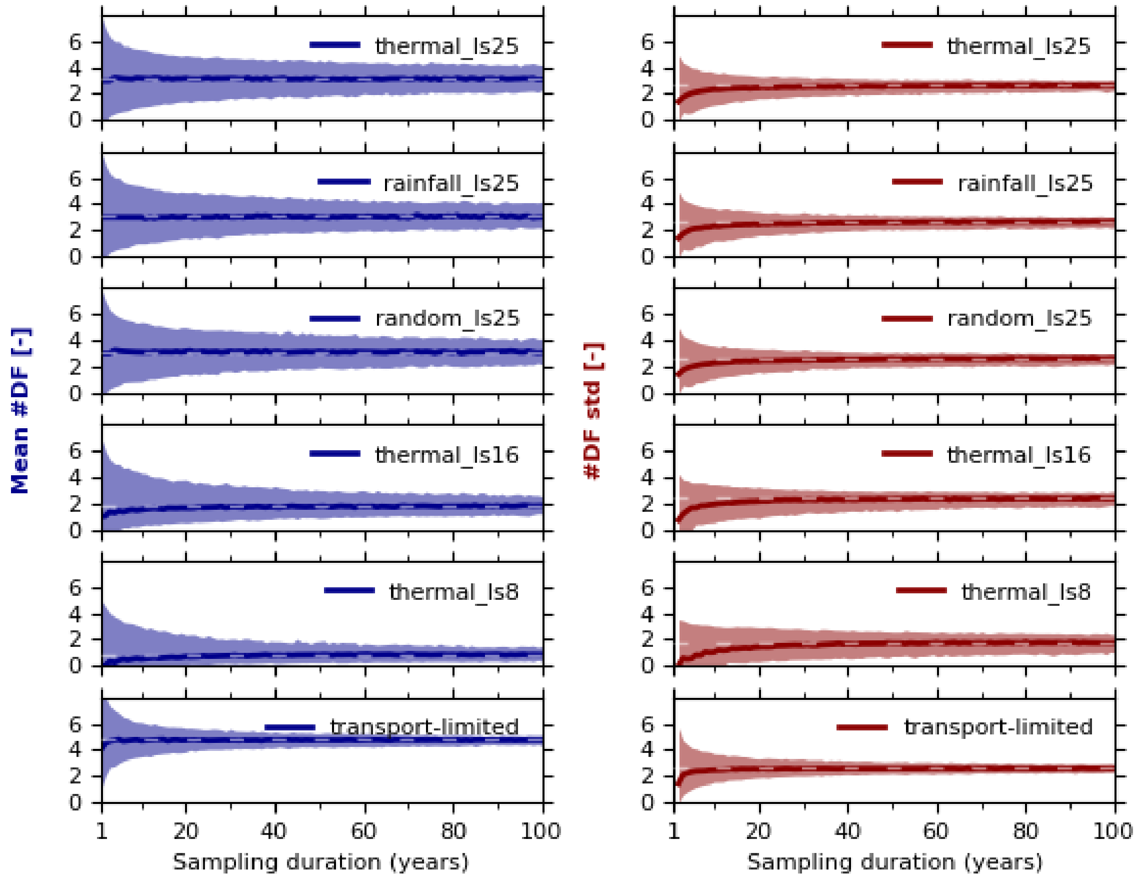

Figure S4. Number of debris flows for all scenarios as a function of record duration. The median (solid line) and the 5-95 percentile range (shaded area) are shown for all modelled scenarios (Table S1) with SedCas.

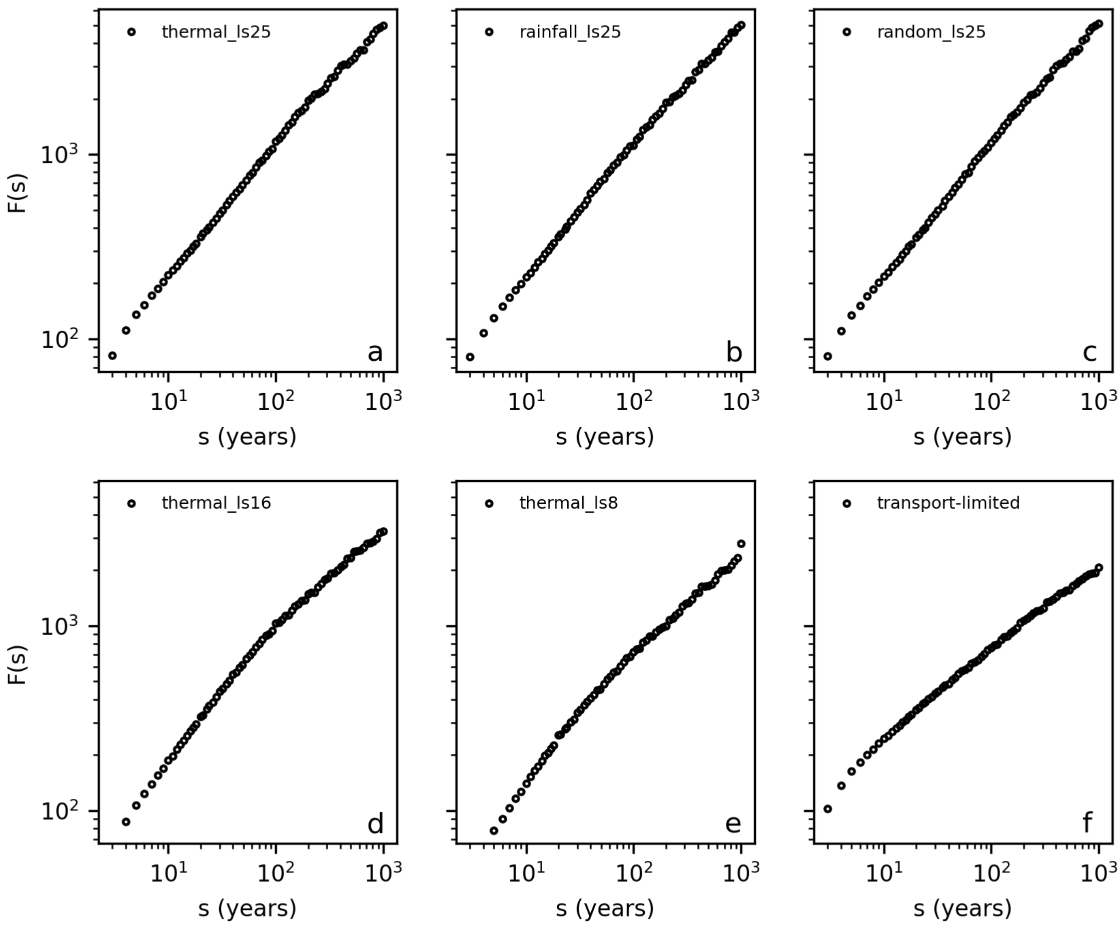

Figure S5. Detrended fluctuation analysis for annual debris flow yields. Each panel refers to one scenario (see Table 1). The corresponding local slopes (exponent α) are reported in Fig. 4.

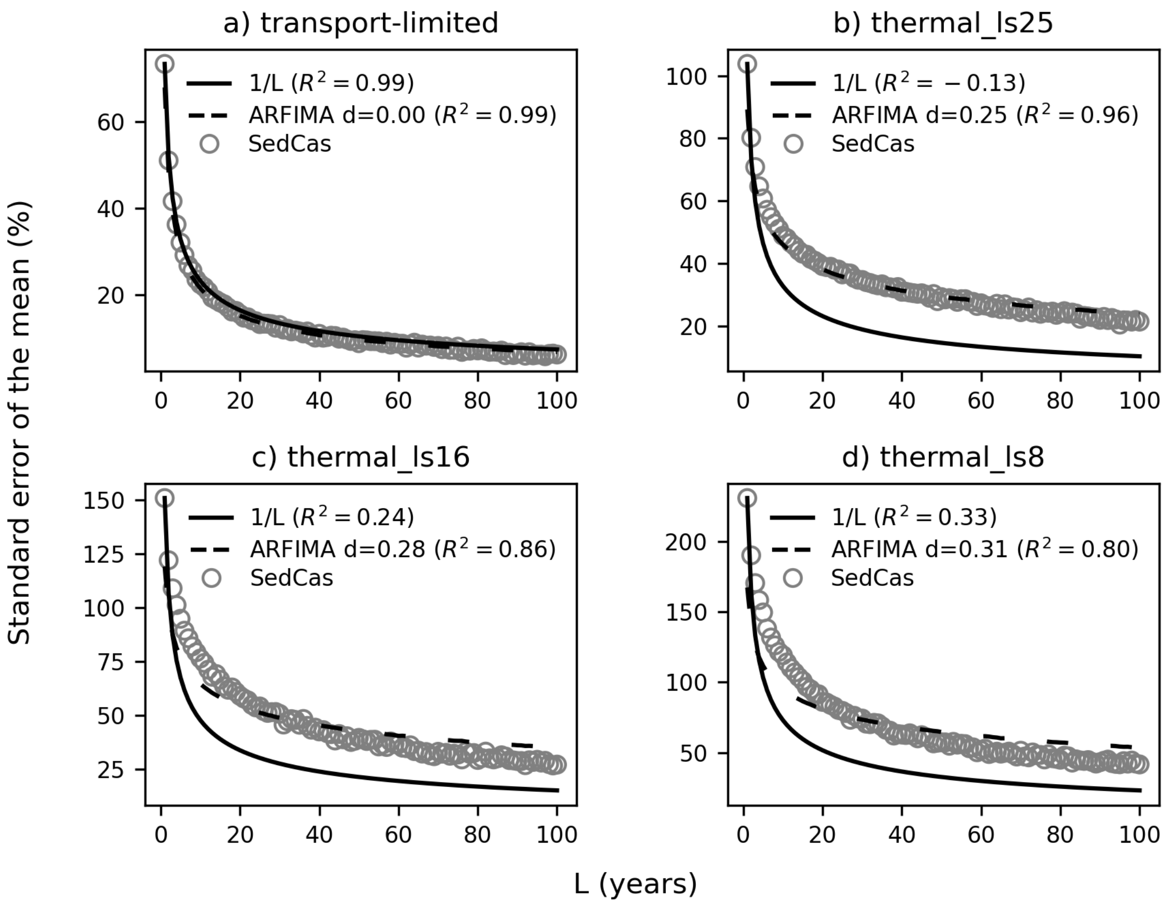

Figure S6. The drop of the standard error in annual debris-flow yields with record length (L) computed with SedCas. The solid black line marks the theoretical drop in standard deviation inversely to record length, if the annual yields were independent and identically distributed random variables. The dashed black line shows the drop from a stochastic time series with long-term memory generated with ARFIMA (Fatichi, 2021). The intensity of long-term memory increases with the *d* parameter (Montanari et al., 1997) and was fitted to the SedCas data.

Table S1. List of model scenarios and their parameterizations. Model runs differ only in the landslide triggering mechanism and climatic threshold for triggering of hillslope landslides. The corresponding parameters are the hillslope landslide triggering mechanism (LS_{trig}) and the thresholds for snow depth (T_{FC-SD}) and temperature (T_{FC-T}) for landslides to be triggered by frost-weathering, and the rainfall threshold for landslides (T_R).

Scenario	Parameters				Description
	LS_{trig}	T_{FC-SD} (mm SWE)	T_{FC-T} (°C)	T_R (mm/d)	
thermal_ls25	frost-weathering	11	-0.5	-	Reference, as calibrated in Hirschberg et al. (2021a)
rainfall_ls25	rainfall	-	-	7.9	Hillslope landslides triggered by a daily rainfall threshold
random_ls25	random	-	-	-	Hillslope landslides occur with random temporal spacing (log-normal)
thermal_ls16	frost-weathering	11	-2.2	-	Reduced sediment supply by ∼1/3 (16 instead of 25 yearly landslides on average) by adjusting T_{FC-T}
thermal_ls8	frost-weathering	11	-4.2	-	Reduced sediment supply by ∼2/3 (8 instead of 25 yearly landslides on average) by adjusting T_{FC-T}
transport-limited	-	-	-	-	Sediment transport follows the transport capacity computed with the SedCas hydrological module