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

Jacob Hirschberg[1,2], Brian W. McArdell[1], Georgina L. Bennett[3], and Peter Molnar[2]

[1]WSL, Swiss Federal Institute for Forest, Snow and Landscape Research, Birmensdorf, Switzerland

[2]Institute of Environmental Engineering, ETH Zurich, Zurich, Switzerland

[3]Geography, University of Exeter, Exeter, United Kingdom

Contents of this file

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

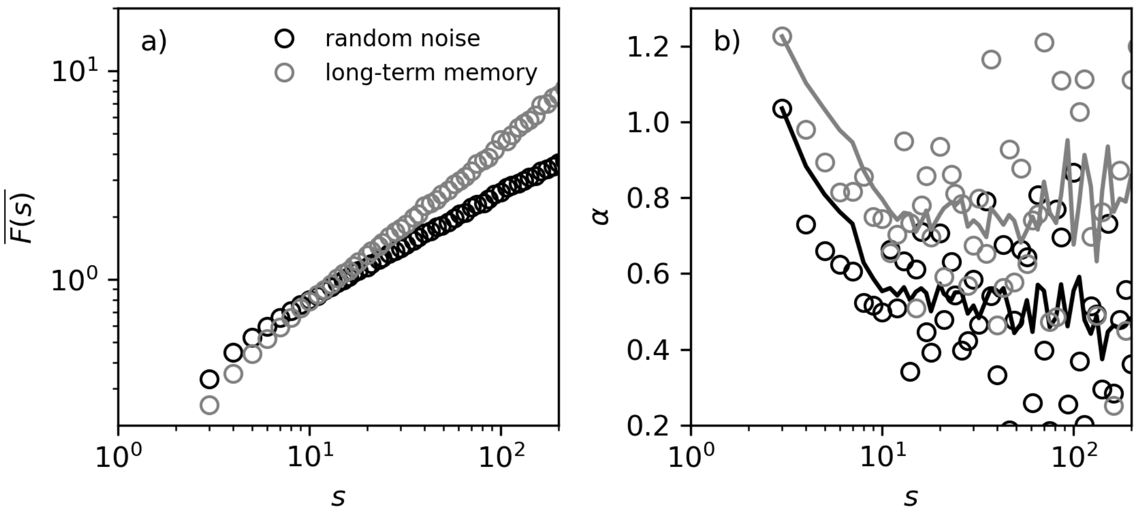

Figure S1. Example DFA analysis using fractional Gaussian noise without (random noise, $\alpha = 0.5$) and with long-term memory ($\alpha = 0.75$). (a) scaling of the mean spread $\overline{F(s)}$ with sampling record length s; (b) local slope (exponent α) computed from the $s - \overline{F(s)}$ pairs.

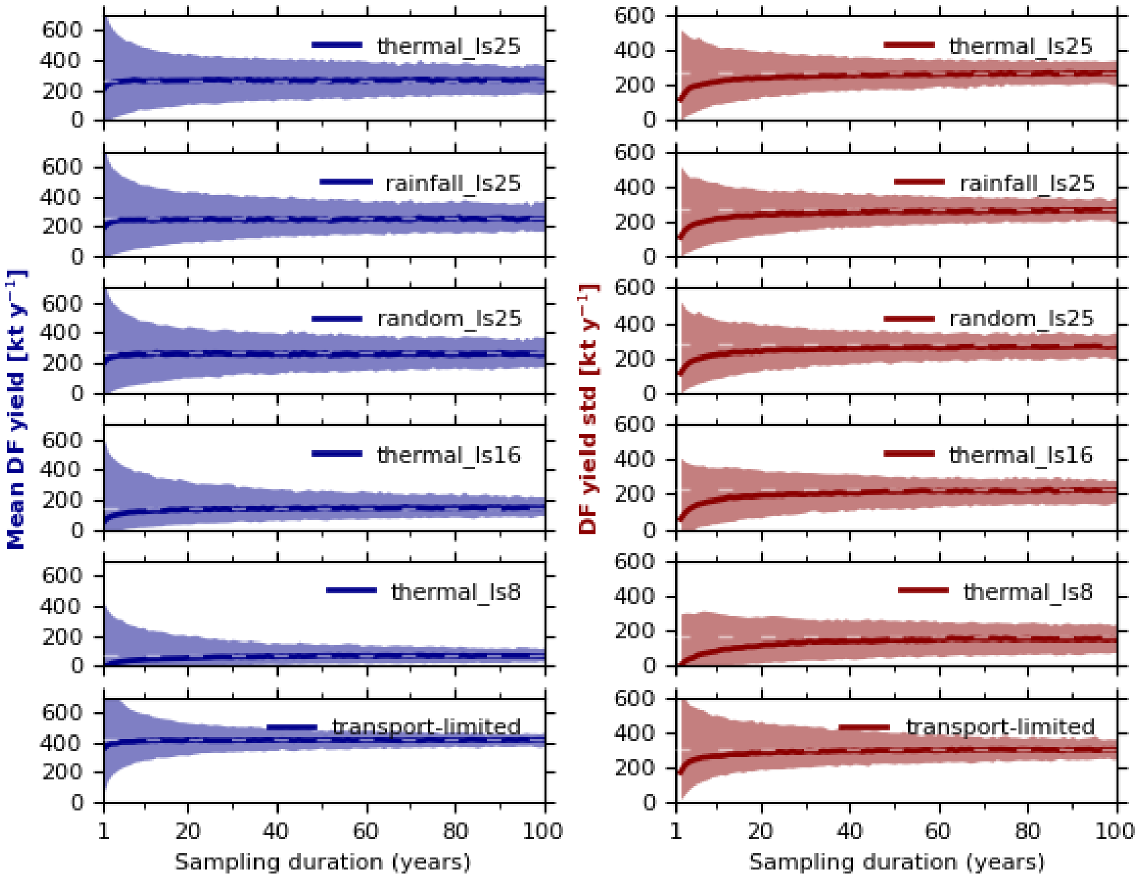

Figure S2. Debris-flow yields for all scenarios as a function of record duration. The median (solid line) and the 5-95 percentile range (shaded area) are shown for all modelled scenarios (Table S1) with SedCas.

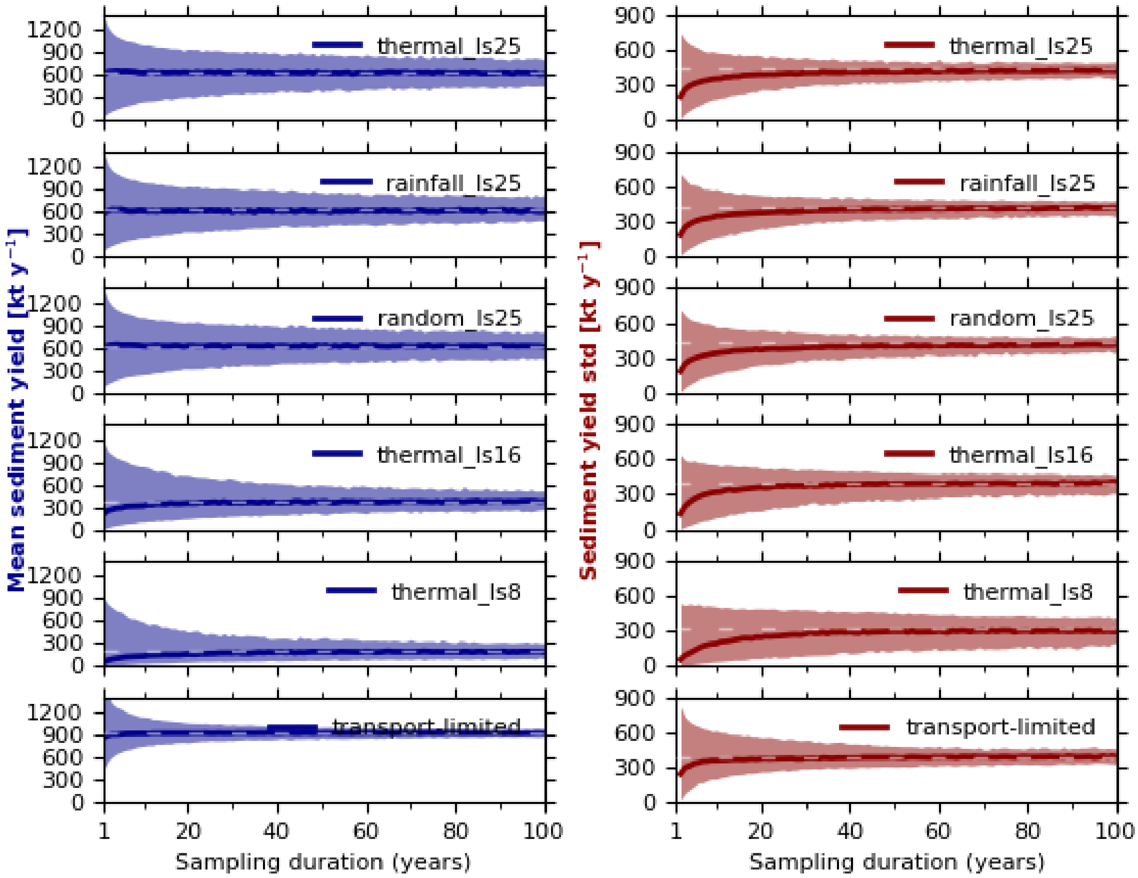

Figure S3. Sediment yields for all scenarios as a function of record duration. The median (solid line) and the 5-95 percentile range (shaded area) are shown for all modelled scenarios (Table S1) with SedCas.

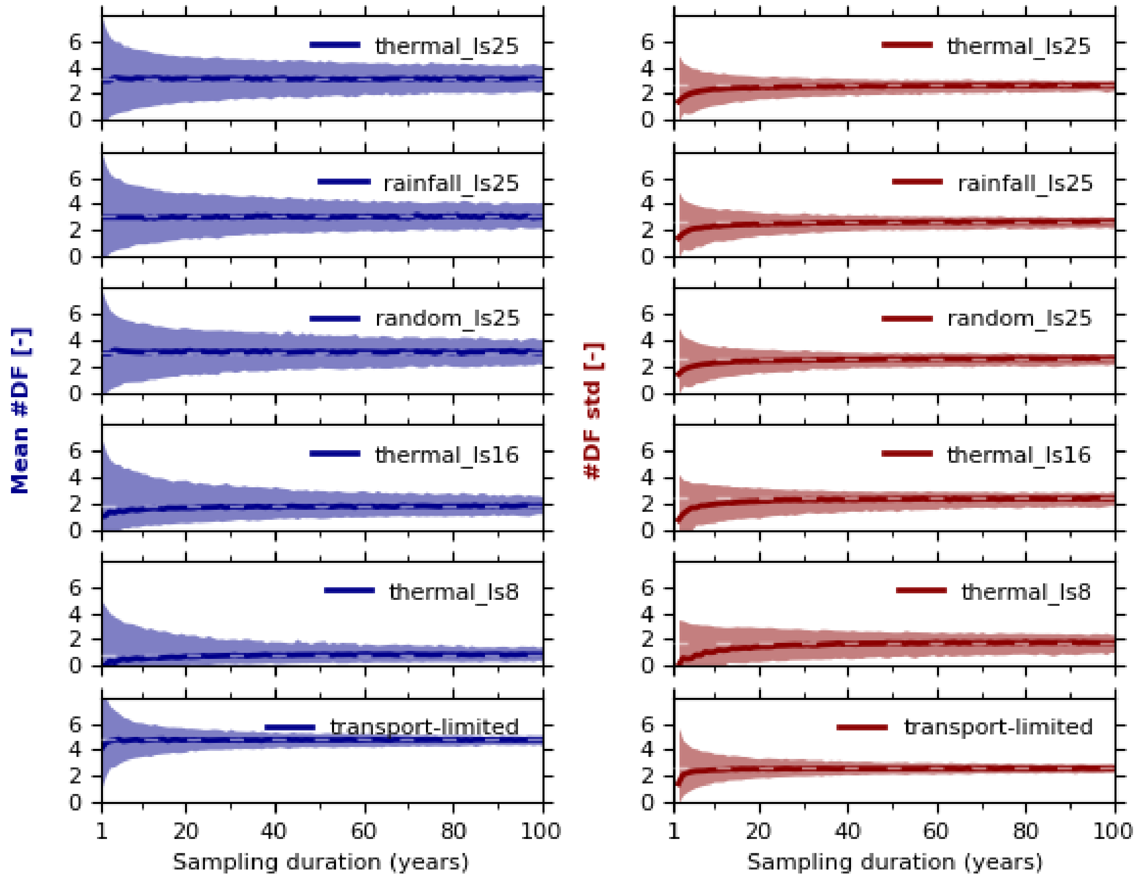

Figure S4. Number of debris flows for all scenarios as a function of record duration. The median (solid line) and the 5-95 percentile range (shaded area) are shown for all modelled scenarios (Table S1) with SedCas.

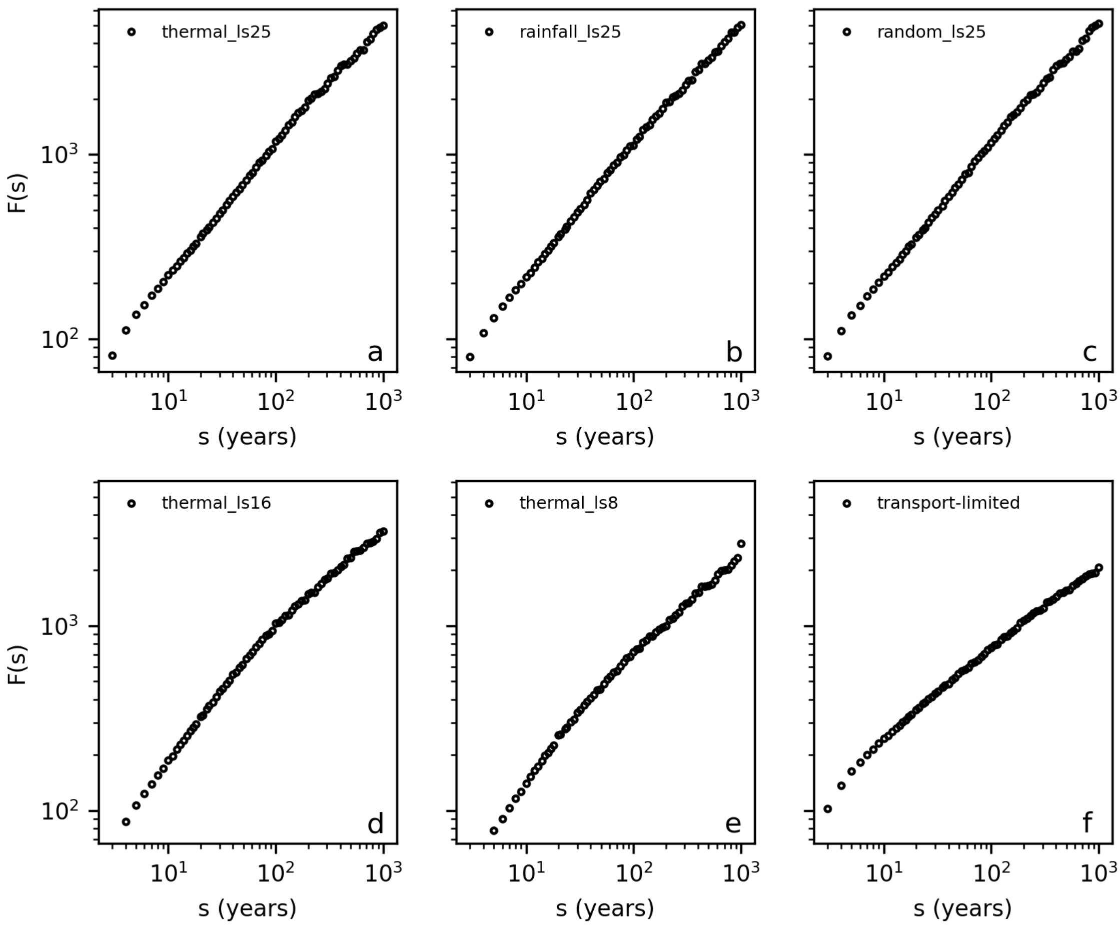

Figure S5. Detrended fluctuation analysis for annual debris flow yields. Each panel refers to one scenario (see Table 1). The corresponding local slopes (exponent α) are reported in Fig. 4.

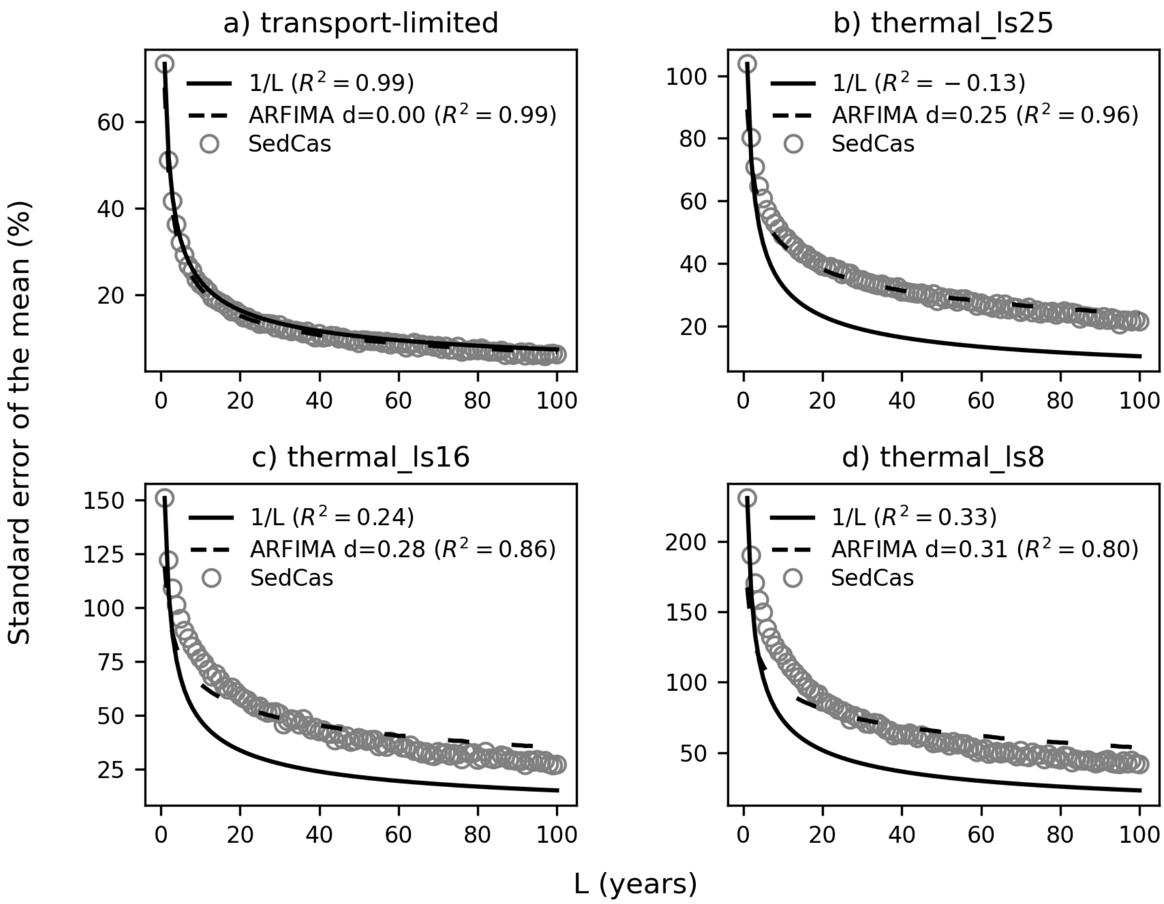

Figure S6. The drop of the standard error in annual debris-flow yields with record length (L) computed with SedCas. The solid black line marks the theoretical drop in standard deviation inversely to record length, if the annual yields were independent and identically distributed random variables. The 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