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Numerical Investigation of Sediment-Yield Underestimation in Supply-Limited Mountain Basins With Short Records

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Key Points:

- Long-term sediment flux simulations (10k years) at hourly resolution are studied under stochastic climatic forcing
- Sediment yield estimates from short records (<30 years) are highly uncertain and likely underestimated
- Sediment yield is affected by sediment supply and sediment storage but does not reflect the exact timing of sediment-input events

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Climate and sediment supply are critical for geomorphic systems. It is known that complex relations between such forcings and sediment mobilization may lead to dampened or erased environmental signals in sediment records. But it is unclear under which circumstances environmental signals are transmitted and measurable downstream. We used a numerical approach consisting of 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). We show that sediment yields estimated from short records are highly uncertain both in terms of mean and interannual variability. Furthermore, sediment yields tend to be underestimated in supply-limited systems, where also long-term memory effects, driven by the history of sediment storage, are evident. Consequently, determining geomorphic system response from short records may be grossly inaccurate and should be extended with sediment supply detection and uncertainty analysis.

Plain Language Summary Whether or not environmental signals, such as climate change or extreme events, are measurable in the sediment output of a basin is a timely question. Climate change affects processes related to sediment production and transport. However, because relations between these are complex, it is questionable if environmental signals are transmitted and measurable in the downstream sediment discharge. Here, we used a numerical approach for a geomorphic system; the Illgraben debris-flow catchment in the Swiss Alps. We coupled a sediment cascade model and a stochastic weather generator to study the detectability of change in sediment yield under a range of conditions, such as different sampling durations and mean erosion rates. We show that sediment yields estimated from short records are highly uncertain and that the history of sediment supply and storage matters. These effects should be included in assessments of change in geomorphic systems.

1. Introduction

The study of erosion rates and sediment yields is fundamental for understanding landscape response to environmental signals such as climate and land use change (e.g., Adams et al., 2020; Bookhagen & Strecker, 2012; Borrelli et al., 2017; Molnar & England, 1990), for deciphering sedimentary records (e.g., Castelltort & Van Den Driessche, 2003), and for predicting hazards and risks connected to sediment transport processes (e.g., Jakob et al., 2005) or riverine ecological habitat (e.g., Evans et al., 2006). Comparing short-term sediment yields estimated from sediment load measurements, with long-term estimates inferred from cosmogenic radionuclide concentrations, has revealed some discrepancies depending on basin size and the dominant erosional process (Covault et al., 2013). Short records may miss 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 of sediment yields especially in small, natural basins with little opportunity for sediment storage, while larger basins may 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.

Climate and land cover change affect hillslope erosion, but these environmental signals may be dampened, delayed or erased in the sediment output (Armitage et al., 2013; Jerolmack & Paola, 2010; Simpson & Castelltort, 2012). Field, experimental and numerical studies suggest that the stratigraphy generally records ordinary rather than extreme sediment transport rates (Ganti et al., 2020; Paola et al., 2018; Sadler & Jerolmack, 2015), but also that environmental signals may manifest in other features, such as grain size patterns (Armitage et al., 2011; D'Arcy et al., 2017). Thereby, the frequencies and magnitudes of forcings compared to system response timescales is

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of importance for signal preservation (Jerolmack & Paola, 2010). However, it is still debated how and which types of geomorphic systems preserve or erase environmental signals. Furthermore, human activities such as damming and flushing of trapped sediments complicate the analysis of sediment flux records in large basins (Costa et al., 2018; Lane et al., 2019). Consequently, numerical models are needed to study the geomorphic response to variable climate forcing to explore the cause-and-effect relations in geomorphic systems (e.g., Armitage et al., 2011; Coulthard & Van De Wiel, 2013; Godard & Tucker, 2021; Tucker & Bras, 2000; Van De Wiel & Coulthard, 2010). The effect of changes in mass movements and their impact on sediment fluxes on shorter timescales has received little attention in modeling, despite the direct implications for climate change impact and hazard assessment.

Herein we focus on steep headwater catchments characterized by mass-wasting processes such as debris flows (e.g., Bennett et al., 2013; Dietrich & Dunne, 1978). We use a stochastic process-informed geomorphic modeling framework to quantify uncertainties in sediment yield estimates. With numerical experiments we study (a) the sensitivity of sediment yield estimates to the length of the observational record, and hence how many years of measurements are needed for a reliable estimate; (b) how the sediment yield depends on the climate forcing combined with the history of sediment supply, and hence how large a change in the sediment supply signal (exact timing and frequency) has to be in order to be detectable in the sediment output; and (c) the evidence and source of multi-year memory effects in sediment yields.

2. Experimental Setup

2.1. Geomorphic System and Climate Forcing Models

We coupled the SedCas sediment cascade model (Bennett et al., 2014; Hirschberg, Fatichi, et al., 2021) and the AWE-GEN stochastic weather generator (Fatichi et al., 2011) to simulate hydrological and sediment fluxes at Illgraben (Swiss Alps). We ran simulations at high temporal resolution (hourly) while spanning geomorphologically relevant timescales (10k years) and a range of sediment supply conditions. This allowed studying first-order impacts of climate and sediment production on sediment yield and debris-flow activity including their uncertainties. Illgraben (4.8 km^2) is a torrent with an average of ~5 debris flows annually, which typically have bulk volumes $\leq 10^5$ m^3 (Hirschberg, Badoux, et al., 2021). In 1961, a rock avalanche (~$3.5 \cdot 10^6$ m^3) increased the debris-flow activity in subsequent years, which also exceeded typical volumes ($2.5–5 \cdot 10^5$ m^3; Gabus et al., 2008; Hürlimann et al., 2003).

The AWE-GEN-SedCas modeling chain was calibrated and tested in Hirschberg, Fatichi, et al. (2021) to assess climate change impacts on sediment yield and debris-flow activity in the 21st century. SedCas is a conceptual geomorphic system model based on the concept of sediment cascades (Bennett et al., 2014; Berger et al., 2011). It consists of two connected sediment reservoirs on the hillslope and in the channel. Sediment leaving the basin is mobilized from the channel reservoir by surface runoff. The mass of mobilized sediment corresponds to the transport capacity of the surface runoff (following a rating curve) if sufficient sediment is available, or else to the mass of available sediment. The water balance is solved by connected linear reservoirs representing hydrological response units. Sediment inputs from hillslopes are either triggered by frost-weathering, rainfall or randomly, whereas only one mechanism is considered per model run. Therefore, the effect of these different mechanisms can be studied. Frost-weathering sets in when the daily mean air temperature drops below a freezing temperature threshold and snow depth is below a threshold to not insulate the bedrock (e.g., Draebing & Mayer, 2021). Rainfall-induced landslides happen when daily rainfall exceeds a threshold (e.g., Leonarduzzi et al., 2017). These larger failures (>233 m^3) are sampled from a power-law distribution which was empirically fitted to observed landslides (Bennett et al., 2012). Smaller landslides occur at random intervals with log-normally distributed spacing. The water and sediment balances are solved at hourly time steps. Hirschberg, Fatichi, et al. (2021) conducted the calibration and sensitivity analysis of SedCas using 17 years of climate and debris-flow observations. SedCas reproduces debris-flow statistics such as frequency, mean and standard deviation of the magnitudes, as well as seasonal patterns in sediment yields.

AWE-GEN generates the stochastic climatic forcing of SedCas. It produces hourly time series of correlated weather variables (e.g., precipitation, air temperature) at a point representing the catchment mean elevation. It was calibrated against a weather station in the vicinity (11 km) of Illgraben (Hirschberg, Fatichi, et al., 2021).

Table 1
List of Modeled Scenarios

Scenario	Parameters					Description
	LS_{trig}	$T_{FC-\mathrm{SD}}$ (mm SWE)	T_{FC-T} (°C)	T_R (mm d^{-1})	n_{LS} (y^{-1})	
1 (REF)	Frost-weathering	11	−0.5	-	25	Reference, as calibrated in Hirschberg et al. (2021a)
2	Rainfall	-	-	7.9	25	Hillslope landslides triggered by a daily rainfall exceeding threshold T_R
3	Random	-	-	-	25	Hillslope landslides occur with random temporal spacing (log-normal)
4	Frost-weathering	11	−2.2	-	16	Reduced sediment supply by ~1/3 by adjusting T_{FC-T}
5 (SL)	Frost-weathering	11	−4.2	-	8	Reduced sediment supply by ~2/3 by adjusting T_{FC-T}
6 (TL)	Unlimited supply	-	-	-	-	Sediment transport follows the transport capacity computed with the SedCas hydrological module

Note. Scenarios differ only in the mechanism (LS_{trig}) and climatic threshold for hillslope landslide triggering. The SedCas parameters governing the triggering are the snow-depth ($T_{FC-\mathrm{SD}}$) and temperature (T_{FC-T}) thresholds for frost-weathering, and the rainfall threshold (T_R). These parameters are set to result in the desired mean number of landslides per year (n_{LS}).

AWE-GEN reproduces extremes as well as inter-annual variability of climate variables because climate statistics are aggregated at a range of temporal scales (from hourly to annual) in the calibration. We have ensured that the coupling of AWE-GEN with SedCas on average reproduces the frequency of hillslope landslides triggered by frost-weathering and the number of debris flows at the basin outlet (Hirschberg, Fatichi, et al., 2021).

2.2. Modeled Scenarios

To study the sensitivity of sediment yield estimates to sediment supply mechanisms and sediment supply mass limitations, and to test if changes therein are detectable in the model output, we ran SedCas under six scenarios (Table 1). A supply-limited system is defined as a system in which available sediment volume in the hillslope-channel storage is frequently less than the volumetric transport capacity associated with a runoff event. The calibrated setup with frost-weathering and the mean number of yearly sediment supply events from hillslopes to the channel ($n_{LS} = 25$), served as a reference (Scenario 1, REF). To study the effect of the timing of sediment supply, and decouple it from air temperature, we ran simulations with the same n_{LS}, but triggered by rainfall and randomly (Scenarios 2 and 3). For simulating stronger sediment supply limitations, we lowered the temperature limit for frost-weathering so that n_{LS} decreased by 1/3 (Scenario 4) and 2/3 (Scenario 5, SL) compared to REF. We additionally considered a transport-limited scenario (Scenario 6, TL) to quantify signals in the sediment yield introduced by climate variability alone.

All scenarios were forced with the same 10k-year hourly climate simulated with AWE-GEN and therefore the hydrological variables (e.g., discharge) are identical among the scenarios. When the condition for a hillslope landslide was met, the magnitude (mass) was sampled from the same distribution (for illustrations of these distributions and an example time series, see Figure S1 in Supporting Information S1). The simulated channel sediment storage develops in cycles of transport-limited and supply-limited conditions and does not show any long-term storage beyond 10k years. The differences in sediment supply result in distinct distributions of annual sediment yields.

2.3. Analysis of Long-Term Simulations

Each scenario simulation (Table 1) was resampled to quantify uncertainties in annual sediment yields and their interannual variability. The full time series was split into subsets of 1–100 years, and the mean and variance of annual sediment yields were estimated for each subset. This allowed for analyzing (a) the effects of short records on the uncertainties of sediment yield estimates, and (b) the detectability of scenario-dependent differences in sediment input rate and mechanism.

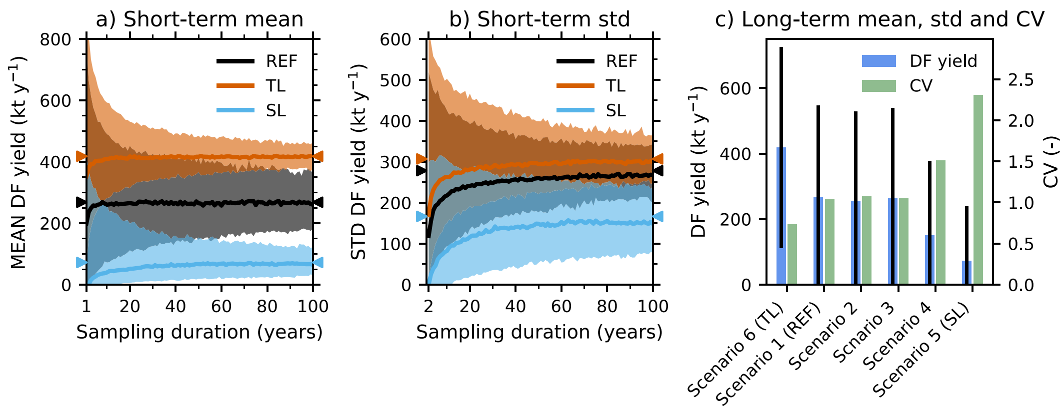

Figure 1. Sensitivity to record duration for (a) mean and (b) standard deviation of annual sediment yields for three scenarios. The medians (solid line) and the 5th–95th percentile range (shaded area) were computed by resampling the long-term (10k-year) simulations, the mean and standard deviation of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

When large amounts of sediment are delivered from the hillslopes to the channel, these may be temporarily stored and transferred to the outlet in a series of subsequent discharge events, possibly over a long period of time. This creates a memory effect in the sediment output dependent on the history of the hillslope-channel fluxes. To identify and quantify these, we analyzed long-term correlation in annual sediment yields using detrended fluctuation analysis (DFA, Peng et al., 1994) in Python (Rydin & Hassan, 2021). DFA is a technique to identify scaling properties in fluctuating or non-stationary time series, for example, 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 an uncorrelated random time series (white noise) results in $\alpha = 0.5$, while time series with long-term memory manifest in $\alpha > 0.5$ (Figure S2 in Supporting Information S1). When plotting α as a function of s, that is, the local slope from the $s - \overline{F(s)}$ plots, the representative timescales and scaling properties can be identified visually (Figure S2 in Supporting Information S1; Bryce & Sprague, 2012). We also fitted a stochastic process with long-term memory (ARFIMA) to the annual 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

Results are presented for annual sediment yields and correspond to the mean mass of sediment exported from the catchment by all debris flows per year. The estimated mean annual sediment yield ($\hat{\mu}$) can be both greatly over- or underestimated in all scenarios if based on short records (<20 years; Figure 1a). The uncertainty is largest for REF, where $\hat{\mu}$ can be biased by a factor of ±2 even after 30 years. Although uncertainty bounds of $\hat{\mu}$ may overlap even after 50 years, the different scenarios result in statistically distinguishable equilibria, that is, stable sediment yields. Thus, sediment-supply regime changes are likely to be identified after ∼30 years. Underestimating $\hat{\mu}$ in short records is most likely for the SL scenario.

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 1b). However, $\hat{\sigma}$ is underestimated in all scenarios for short records, and this effect is stronger for supply-limited scenarios. As a consequence, observations of ∼30 years are necessary for stable $\hat{\sigma}$, especially for supply-limited conditions. Repeating the same analysis for the annual total sediment yield (including bedload transport) and the annual number of debris flows resulted in the same patterns (Figures S4 and S5 in Supporting Information S1).

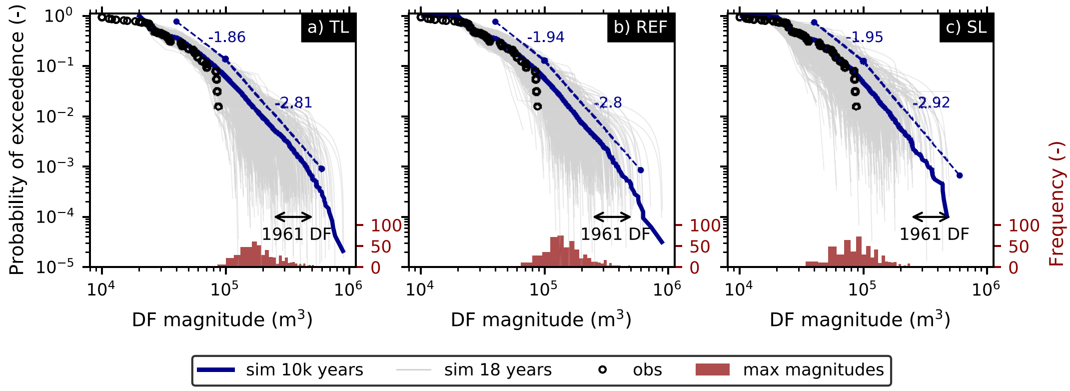

Figure 2. Debris-flow magnitude-frequency distributions. The blue solid lines were estimated from the 10k-year simulations and the gray lines from 18-year-long subsets thereof, which corresponds to the time period of the observations (black circles). Slopes (i.e., power-law exponents) were fitted to the 10k-year simulations for two magnitude ranges (dashed blue lines). The histograms show the largest debris-flow magnitudes (95th percentile) from the simulation subsets. The range of volume estimates from large destructive debris flows in 1961 are indicated by the black arrows.

The scenarios with the same number of landslides as REF but different triggering mechanisms showed very similar results (Scenarios 2 and 3 in Figures 1c and S3 in Supporting Information S1). This means that the differences in the timing and seasonality of sediment supply between these scenarios were not transmitted to the outlet (i.e., invisible in $\hat{\mu}$). Although the climate forcing remained the same among the scenarios, reductions in sediment supply increased the coefficient of variation (CV) in annual sediment yields from 0.7 in TL, to ∼1 for the scenarios with $n_{LS} = 25$ and to 1.5 and 2.3 for the more supply-limited scenarios (Figure 1c). Therefore, reducing the sediment supply had a clear effect by diminishing mean sediment yields and increasing interannual variability.

3.2. Debris-Flow Distributions

Short records also affect hazard assessment. Magnitude-frequency (MF) distributions were estimated for simulated debris-flow event volumes for three scenarios (REF, SL, TL) and compared with observations from 18 years (Figure 2). The simulation-based distributions are characterized by power-law tails and range from $\sim 10^4$ to 10^6 m^3. The observations lie within the simulated uncertainties. The simulated magnitudes tend to overestimate observations, which is attributed to the temporal rainfall structure generated with AWE-GEN and the resulting higher transport capacity in these extreme events (Hirschberg, Fatichi, et al., 2021). Due to the similar power-law tails, 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 (red histograms in Figure 2) are significantly different between the scenarios and point to the fact that the observations are more likely to result from a supply-limited scenario. The observations reach an upper limit at $8 \cdot 10^4$ m^3, although, the simulations and independent observations from 1961 both suggest the possibility of much larger events, which are mostly absent in short records.

3.3. Long-Term Memory Effects in Sediment Fluxes

Transient sediment supply and its effect on sediment storage 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 S6 in Supporting Information S1). The presence of long-term memory is evident in the simulations with stable slopes around $\alpha \approx 0.75$ between ∼8–50 years for the scenarios with $n_{LS} = 25$ (Figures 3a, 3d and 3e). The scenarios with decreased sediment supply had shorter (∼8–20 years) but steeper ($\alpha > 0.75$) stable slopes, which indicate stronger long-term memory at these timescales (Figures 3b and 3c). The increased spreads in α after 20–50 years indicate weakening memory, that is, random signals at longer timescales. Interestingly, the TL scenario differs from all the others because α stabilizes at 0.5 already for small s. Hence, there are no long-term memory effects

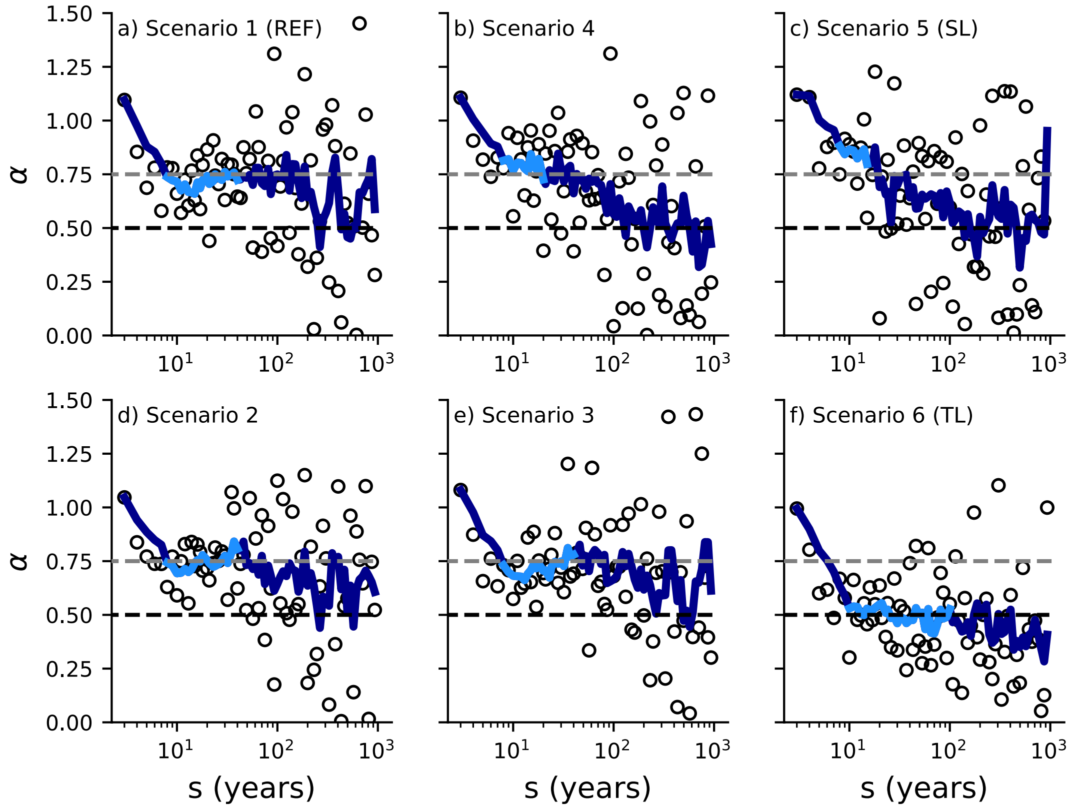

Figure 3. Local slope (exponent α) of the $s - \overline{F(s)}$ relation in sediment yields shown in Figure S6 in Supporting Information S1 as a function of sampling duration s. The upper row shows the reference (a) and the reduced sediment supply scenarios (b, c). The lower row shows the scenarios with hillslope landslides triggered by rainfall (d), randomly (e) and the transport-limited scenario (f). The dots represent the slope between two individual points in the $s - \overline{F(s)}$ plot 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 $\alpha = 0.5$ shows the condition of no long-term correlation. The dashed gray line at $\alpha = 0.75$ shows the condition with strong long-term memory.

in the sediment output induced by climate alone when sediment availability is unlimited. The high values of α for $s < 8$ years is an expected methodological bias without physical meaning (Peng et al., 1994).

4. Discussion

4.1. Short-Long-Term Discrepancy in Sediment Yield Estimates

We quantified sediment flux magnitude and variability over geomorphologically relevant timescales in Illgraben and in stationary climate conditions. We numerically investigated the influence of the record length used to estimate the mean ($\hat{\mu}$) and the standard deviation ($\hat{\sigma}$) of annual sediment yields. Short records (<30 years) resulted in $\hat{\mu}$ and $\hat{\sigma}$ which were uncertain within a factor of ± 2. While the reference scenario suggests that the likelihood of over- or underestimation of $\hat{\mu}$ was balanced in supply-limited scenarios, $\hat{\mu}$ was likely to be underestimated in 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 statistical theory, but compounded by the fact that for supply-limited scenarios, the long-term memory was stronger (Figure 3). Therefore, interannual variability in sediment yields is expected to be underestimated in short records and geomorphic systems with memory.

Discrepancies between short- and long-term estimates of sediment yield have been attributed to low-frequency high-magnitude pulses of erosion (e.g., Kirchner et al., 2001). We are able to identify what causes the discrepancy in our simulations, although the explanation may be different in other geomorphic systems. We argue that if the discrepancy was caused by extreme rainfall events leading to large debris flows, it would be visible in all scenarios because they were forced with the same climate. Instead, the discrepancy was driven by the sequencing

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of large hillslope sediment supply events. These events occur as a combination of climatic hillslope landslide triggering conditions (e.g., many days with frost-weathering conditions) and the inherent randomness of landslide magnitudes. Consequently, large sediment evacuation events by debris flows may occur both in transport- and supply-limited systems, but more rarely in the supply-limited case, where the likelihood of having debris-flow triggering runoff and ample sediment availability at the same time is lower. We acknowledge that hydrological connectivity may be an important limiting factor for sediment flux even in small basins (Reid et al., 2007) and therefore SedCas, as a spatially-lumped model, may not be ideal to study the impact of single extreme events. Nevertheless, the simulated dynamics reflect observations made 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), which can lead to elevated sediment yields even at the 10^3-year timescale (Korup, 2012).

4.2. Implications for Hazard Assessment and Mitigation

Our findings point to challenges in the assessment of hazard and climate change impacts on sediment flux, and in the design of engineering structures (e.g., sediment retention basins). We showed that the sediment yield signal is inherently noisy even under stationary climatic conditions, and climate change adds a non-stationary forcing. Short records of sediment observations will further challenge the detection and prediction of significant changes. 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 1) and to the possible underestimation of large debris flows (Figure 2). In basins with short records, additional information for longer timescales should be consulted. For example, 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 complement MF distribution fitting. Effort has also 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 modeling frameworks, as presented here, are helpful for extending MF distributions beyond short-term observations (Figure 2).

4.3. Preservation of Climate Signals in Sediment Records

The sediment supply mechanism (frost-weathering, rainfall or random) in our system had no effect on the long-term sediment yield estimates. These mechanisms mainly differ in the timing and seasonality of sediment production. For example, frost-weathering is most active in cold months while intense rainfall mainly occurs in warm months. In our framework, the MF distributions of sediment supply events are identical, and the temporal distribution of these events, driven by the climatic conditions favoring frost-weathering or rainfall induced landslides, did not induce a large enough change in sediment supply dynamics to affect the annual sediment yields. As a consequence, these signals in sediment supply were erased in the output.

It has been argued that environmental signals will only be recorded and identified in the sedimentary records if their timescale exceeds the system response time (Castelltort & Van Den Driessche, 2003; Hoffmann, 2015), unless the magnitude of the signal exceeds natural variability (Jerolmack & Paola, 2010). For Illgraben and similar basins this means that a sufficiently large change needs to persist for >30 years. This may seem short, but because this catchment's erosion rate exceeds other Alpine sites by about one order of magnitude (Delunel et al., 2020; Stutenbecker et al., 2018) and the basin has relatively little opportunity to store sediment, this timescale must be much larger in other basins, where storage opportunities exist and other processes dominate, such as glacial periods (e.g., Ganti et al., 2016; Hoffmann, 2015).

We've shown that long-term memory effects may be evident in the sediment discharge for decades under stationary conditions (Figure 3). To test if these memory effects are induced by the sequence of elevated sediment yields or by the absence of mobilizable sediments, we converted the simulated annual sediment yield time series of all scenarios into binary 0–1 series, discounting the actual sediment magnitude, and recomputed α (Figure S7 in Supporting Information S1). Because α only slightly decreases compared to when simulated sediment yield magnitudes were used, we conclude that the main reason for the long-term memory in annual sediment yields is the sequence and clustering of sediment supply events in-between periods without any debris flows.

Long-term memory is also evident from the uncertainty in $\hat{\mu}$ (Figure 1a). The drop in uncertainty is inversely related to s for TL, as it is expected for a random, independent variable, while the drop for the other scenarios is much slower (Figure S8 in Supporting Information S1). A similar decrease in the uncertainty for those scenarios could only be reproduced by fitting a stochastic process with long-term memory ($H > 0.5$) to the data (e.g., ARFIMA model in Figure S8 in Supporting Information S1). Like in the DFA analysis, the TL time series behaves differently and confirms that the long-term memory in the supply-limited scenarios is induced by different sediment supply regimes.

This study is limited to Illgraben and the hydro-geomorphic processes built into SedCas. Future work should focus on exploring the behavior of other geomorphic systems with different sediment supply regimes, climatic forcing, erosion rates, and using other geomorphic models. For example, systems with stronger glacial and permafrost-related characteristics. We have shown that the framework with stochastic climatic forcing and numerical geomorphic system modeling is suitable for exploring possible cause-and-effect relations between sediment supply and output, which are not easily discernible from observations alone.

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 studies, we showed that estimates of mean annual sediment yield may be underestimated in 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. Such cycles also cause long-term memory in sediment output at timescales of up to ∼50 years. Consequently, the interannual variability of sediment yield estimates was underestimated if sediment supply was limited. Furthermore, the signal from changing sediment supply mechanisms (triggering conditions), which affect the timing and seasonality of sediment inputs, was erased in the sediment output. In similar systems, climate change impacts on sediment supply may therefore only be detected in the sediment output after >30 years and if the erosion rate is considerably altered. The results highlight the importance of combining stochastic forcing of sediment fluxes with memory-dependent storage to predict the state and response of geomorphic systems. This will support decision making in natural hazard and climate change impact assessments, especially if they are based on short records.

Data Availability Statement

The Illgraben debris-flow data is available from the EnviDat repository (McArdell & Hirschberg, 2020). The SedCas model code is available from an open-source repository (Hirschberg et al., 2022b). The input data for SedCas generated with AWE-GEN as well as the SedCas output data is available from the EnviDat repository (Hirschberg et al., 2022a). The AWE-GEN model is described in Fatichi et al. (2011) and can be downloaded from https://hyd.ifu.ethz.ch/research-data-models/awe-gen.html.

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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). https://doi.org/10.1126/sciadv.aaz3166

Armitage, J. J., Duller, R. A., Whittaker, A. C., & Allen, P. A. (2011). Transformation of tectonic and climatic signals from source to sedimentary archive. *Nature Geoscience*, *4*(4), 231–235. https://doi.org/10.1038/ngeo1087

Armitage, J. J., Dunkley Jones, T., Duller, R. A., Whittaker, A. C., & Allen, P. A. (2013). Temporal buffering of climate-driven sediment flux cycles by transient catchment response. *Earth and Planetary Science Letters*, *369–370*, 200–210. https://doi.org/10.1016/J.EPSL.2013.03.020

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. https://doi.org/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. https://doi.org/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. https://doi.org/10.1016/j.geomorph.2012.11.029

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. https://doi.org/10.1016/j.geomorph.2010.10.019

Bookhagen, B., & Strecker, M. R. (2012). 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. https://doi.org/10.1016/J.EPSL.2012.02.005

Borrelli, P., Robinson, D. A., Fleischer, L. R., Lugato, E., Ballabio, C., Alewell, C., et al. (2017). An assessment of the global impact of 21st century land use change on soil erosion. *Nature Communications*, *8*(1). https://doi.org/10.1038/s41467-017-02142-7

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

Cannon, S. H., Kirkham, R. M., & Parise, M. (2001). Wildfire-related debris-flow initiation processes, Storm King Mountain, Colorado. *Geomorphology*, *39*(3–4), 171–188. https://doi.org/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. https://doi.org/10.1016/S0037-0738(03)00066-6

Costa, A., Molnar, P., Stutenbecker, L., Bakker, M., Silva, T. A., Schlunegger, F., et al. (2018). Temperature signal in suspended sediment export from an Alpine catchment. *Hydrology and Earth System Sciences*, *22*(1), 509–528. https://doi.org/10.5194/HESS-22-509-2018

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. https://doi.org/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. https://doi.org/10.1086/668680

D'Arcy, M., Roda-Boluda, D. C., & Whittaker, A. C. (2017). Glacial-interglacial climate changes recorded by debris flow fan deposits, Owens Valley, California. *Quaternary Science Reviews*, *169*, 288–311. https://doi.org/10.1016/j.quascirev.2017.06.002

de Haas, T., & Densmore, A. L. (2019). Debris-flow volume quantile prediction from catchment morphometry. *Geology*, *47*(8), 1–794. https://doi.org/10.1130/G45950.1

Delunel, R., Schlunegger, F., Valla, P. G., Dixon, J., Glotzbach, C., Hippe, K., et al. (2020). Late-Pleistocene catchment-wide denudation patterns across the European Alps. *Earth-Science Reviews*, *211*, 103407. https://doi.org/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. https://doi.org/10.1130/0091-7613(2001)029

Draebing, D., & Mayer, T. (2021). Topographic and geologic controls on frost cracking in Alpine Rockwalls. *Journal of Geophysical Research: Earth Surface*, *126*(6), e2021JF006163. https://doi.org/10.1029/2021jf006163

Evans, D. J., Gibson, C. E., & Rossell, R. S. (2006). Sediment loads and sources in heavily modified Irish catchments: A move towards informed management strategies. *Geomorphology*, *79*(1–2), 93–113. https://doi.org/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. https://doi.org/10.1016/j.advwatres.2010.12.013

Gabus, J. H., Weidmann, M., Bugnon, P. C., Burri, M., Sartori, M., & Marthaler, M. (2008). Feuille 1287 Sierre—Atlas géologique de la Suisse 1: 25 000. Carte.

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). https://doi.org/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). https://doi.org/10.1126/sciadv.1600204

Godard, V., & Tucker, G. E. (2021). Influence of climate-forcing frequency on hillslope response. *Geophysical Research Letters*, *48*(18), e2021GL094305. https://doi.org/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. https://doi.org/10.5194/nhess-21-2773-2021

Hirschberg, J., Fatichi, S., Bennett, G. L., McArdell, B. W., Peleg, N., Lane, S. N., et al. (2021). Climate change impacts on sediment yield and debris-flow activity in an Alpine catchment. *Journal of Geophysical Research: Earth Surface*, *126*(1). https://doi.org/10.1029/2020JF005739

Hirschberg, J., McArdell, B. W., Bennett, G. L., & Molnar, P. (2022a). *Data for numerical investigation of sediment yield underestimation in supply-limited mountain basins with short records*. EnviDat. https://doi.org/10.16904/envidat.303

Hirschberg, J., McArdell, B. W., Bennett, G. L., & Molnar, P. (2022b). *SedCas version 1.0*. Zenodo. https://doi.org/10.5281/zenodo.5974907

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

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. https://doi.org/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. https://doi.org/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*, *45*, 2954–2964. https://doi.org/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. https://doi.org/10.3390/hydrology4010007

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

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. https://doi.org/10.1130/0091-7613(2001)029<0591:meoyky>2.0.co;2

Korup, O. (2012). Earth's portfolio of extreme sediment transport events. *Elsevier*, *112*(No. 3–4), 115–125. https://doi.org/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. https://doi.org/10.1103/PhysRevLett.81.729

Lane, S. N., Bakker, M., Costa, A., Girardclos, S., Loizeau, J.-L., Molnar, P., et al. (2019). Making stratigraphy in the Anthropocene: Climate change impacts and economic conditions controlling the supply of sediment to Lake Geneva. *Scientific Reports*, *9*(1), 8904. https://doi.org/10.1038/s41598-019-44914-9

Leonarduzzi, E., Molnar, P., & McArdell, B. W. (2017). Predictive performance of rainfall thresholds for shallow landslides in Switzerland from gridded daily data. *Water Resources Research*, *53*(8), 6612–6625. https://doi.org/10.1002/2017WR021044

Matsoukas, C., Islam, S., & Rodriguez-Iturbe, I. (2000). Detrended fluctuation analysis of rainfall and streamflow time series. *Journal of Geophysical Research*, *105*(D23), 29165–29172. https://doi.org/10.1029/2000JD900419

McArdell, B. W., & Hirschberg, J. (2020). *Debris-flow volumes at the Illgraben 2000-2017*. EnviDat. https://doi.org/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. https://doi.org/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. https://doi.org/10.1029/97WR00043

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

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. https://doi.org/10.1146/annurev-earth-082517-010129

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. https://doi.org/10.1103/PhysRevE.49.1685

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. https://doi.org/10.1016/j.geomorph.2006.10.023

Rydin, & Hassan, G. (2021). *LRydin/MFDFA: v0.4*. Zenodo. https://doi.org/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* (Vol. 404, pp. 69–88). Geological Society Special Publication. https://doi.org/10.1144/SP404.7

Schaller, M., Von Blanckenburg, F., Hovius, N., & Kubik, P. W. (2001). Large-scale erosion rates from in situ-produced cosmogenic nuclides in European river sediments. *Earth and Planetary Science Letters*, *188*(3–4), 441–458. https://doi.org/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. https://doi.org/10.1038/ncomms10951

Simpson, G., & Castelltort, S. (2012). Model shows that rivers transmit high-frequency climate cycles to the sedimentary record. *Geology*, *40*(12), 1131–1134. https://doi.org/10.1130/G33451.1

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. https://doi.org/10.1016/j.gloplacha.2007.03.001

Stutenbecker, L., Delunel, R., Schlunegger, F., Silva, T. A., Šegvić, B., Girardclos, S., et al. (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. https://doi.org/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. https://doi.org/10.1007/s10346-011-0269-5

Tomkins, K. M., Humphreys, G. S., Wilkinson, M. T., Fink, D., Hesse, P. P., Doerr, S. H., et al. (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. https://doi.org/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. https://doi.org/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. https://doi.org/10.1130/G30490.1

Wittmann, H., von Blanckenburg, F., Maurice, L., Guyot, J.-L., Filizola, N., & Kubik, P. W. (2011). 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. https://doi.org/10.1130/B30317.1