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Repose time patterns of debris-flow events in alpine catchments

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Abstract

The omnipresent threat of natural hazards in mountainous regions has led to a risk culture which requires knowledge about the frequency of the considered hazardous process. Observations suggest that the frequency of debris-flow events in a single catchment is, besides climatic thresholds, also controlled by its geological, lithological and geomorphological characteristics. Based on investigations of debris-flow event frequencies from 47 headwater catchments, our results support the classification of recurrence intervals as irregular, clustered or regular, originally proposed by Zimmermann et al. in 1997 (*Eclogae Geologicae Helvetiae*, 90(3), 415–420). However, instead of using geomorphological characteristics, our classification relies on quantitative analyses considering potential dependencies between events based on their inter-event (repose) times. By employing a modified dynamic threshold concept with respect to debris-flow initiation, we show that for irregular frequencies neither climatic nor geomorphological thresholds are altered by the last debris-flow event. For regular and clustered time series, however, mutual dependency between events is reasonable and therefore prompts dynamic changes of climatic as well as geomorphological thresholds.

KEYWORDS

debris flow, event frequency, occurrence patterns, repose time models, trigger concepts

1 | INTRODUCTION

Channels in alpine headwater catchments are regularly prone to heavy rainfall events with catastrophic effects due to flooding of infrastructural facilities or settlements (Fuchs et al., 2015). In contrast to larger foreland rivers, floods in alpine catchments (torrential floods) are very often accompanied by a considerable amount of sediment, which significantly increases the potential loss in relation to the actual climate conditions. Thus, alpine catchments can be considered as temporally variable reservoirs of sediment that can be partially or fully incorporated into the flowing mass when they coincide with a critical precipitation event (Hübl, 2018; Marchi et al., 2019). For this reason, sediment availability has to be regarded as a controlling process variable in alpine catchments for inter-event (repose) intervals of torrential flood events, directly influencing the identification of relevant torrential processes

(e.g., Church & Jakob, 2020; Heiser et al., 2015), the preparatory conditions for triggering mechanism such as the fire-hose effect regarding debris flows (Morino et al., 2018), the assessment of possible impacts and dynamic process behavior (e.g., Mazzorana et al., 2014; Scheidl et al., 2019) or the delineation of areas exposed (e.g., Sturm et al. 2018a, 2018b; Totschnig & Fuchs, 2013), to name but a few. Considered over a long period, sediment availability is also fundamental when focusing on river morphodynamics (Church & Ferguson, 2015), especially in the context of equilibrium configurations of torrential streams (e.g., Ferguson, 2021) or sediment export at the river catchment outlet (e.g., Navratil et al. 2012).

Variations in the sediment availability of alpine catchments were recognized early by the seminal work of Stiny (1931), who distinguished “young debris” (*Jungschutt*) torrents, situated in catchments where the availability of sediment is younger compared to the channel activity, from “old debris” (*Altschutt*) torrents, where the sediment availability is abundant, and no significant increase is expected due to

Micha Heiser and Matthias Schlögl contributed equally to this work.

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recent erosion activities. The concept led to a more general differentiation between supply-limited basins in which sediment supply and channel recharge rates are lower and a substantial time must elapse before the next event becomes possible, and supply-unlimited basins in which an almost unlimited amount of sediment is available (Bergmeister et al., 2009; Bovis & Jakob, 1999). Hübl (2018) concludes that if a catchment-specific threshold of discharge is exceeded, the sediment storage (i.e., its availability) controls the resulting flow type. This is especially true for debris flows, where the fraction of mobilized sediment volume often exceeds the runoff caused by the triggering precipitation (Hungr et al., 2014; Jakob & Hungr, 2005) or dimensionless discharge and Shields stress (Tang et al., 2019), and where past events can alter channel morphology through erosion and deposition (Nyman et al., 2020; Palucis & Lamb, 2017; Rengers et al., 2021). However, in contrast to natural hazard processes where precipitation is the dominant triggering process (e.g., snow avalanches or floods without significant sediment transport), repose times of debris flows may therefore not always be considered independent of previous events. This is either because sediment availability is related to weathering processes contributing to channel refilling between active debris-flow periods (Anderson et al., 2015; Bennett et al., 2014; Jakob et al., 2005; Rengers et al., 2020), or to the temporal and spatial destabilization of the bed and banks by past events (Asano & Uchida, 2016; Bezak et al., 2017; Guthrie, 2015; Lenzi et al., 2004; Palucis & Lamb, 2017).

However, first systematic investigations of debris-flow events in 17 Swiss headwater catchments suggested theoretically at least four different repose time patterns. Depending on the available sediment load, Zimmermann et al. (1997), later discussed by Rickenmann (2016), described debris-flow repose times to follow either more or less regular, rather irregular or purely irregular occurrence patterns. A presumed fourth type is based on the assumption that no historical evidence for the occurrence of debris-flow events exists which, for this reason, is not the subject of this study. As these assumptions have not been further supported by quantitative analyses so far, we present a method that allows us to quantitatively determine the suggested repose time patterns for debris-flow events in a considered catchment. We assume that the different repose time patterns are reflected in the hazard functions of the best-suited probability distributions to describe the likelihood that a debris flow will occur at a certain time lag after the last debris-flow event. For this purpose, we analyzed the frequency distributions of 1217 debris-flow events in 47 catchments. Our results confirm three different groups of alpine catchments according to the repose type: (i) regular (*regular*), (ii) clustered (*rather irregular*), and (iii) irregular (*purely irregular*).¹ We further examine the significance of different repose time distributions in the context of a dynamic triggering concept for debris flows and finally discuss the implications of mutual dependencies between events in the context of natural hazard management.

2 | DATA

Frequency analyses of debris-flow events through time are based on two data sets. The first data set was compiled from scientific literature and technical publications, including debris-flow event series from

22 different catchments. This literature-based data set was further completed by debris-flow event series from another 25 catchments, derived from the Austrian torrential event documentation (Heiser et al., 2019). For the latter, only catchments have been considered for which 80% of all documented torrential events were reported as debris flows and in which at least 10 debris-flow events have been reported since the year 1850 (the anticipated end of the Little Ice Age). As all documented events in the Austrian torrent catalogue caused damage in the so-called spatially relevant area, which is defined as the area where according to the respective spatial planning laws the public authorities are responsible for natural hazard protection (Heiser et al., 2019), we assume that those events must have reached at least a certain threshold magnitude large enough to reach the valley bottom. On the other hand, the compiled debris-flow events from the literature are mostly reconstructed from historical information, which suggests that they also had to reach a certain threshold magnitude to be recorded in the chronicles.

A total of 1217 debris-flow events from 47 different catchments was finally analyzed in our study (Figure 1). Basic information and all data used for this study is digitally available in Heiser et al. (2019). An overview of the applied catchments is provided in Tables 1 and 2, respectively, listing the number of available observations, the corresponding observation period as well as the mean repose times together with its 95% bias-corrected and accelerated bootstrap confidence interval (BCa-CI) (Efron & Hastie, 2016).

3 | METHODS

Date information of the compiled events was first transformed into fractional years:

$$t_i^* = y_i + \frac{t_i^{(*)}}{T^{(*)}}, \quad (1)$$

with t_i^* denoting the fractional year, y_i the year and $t_i^{(*)}$ the Julian day at which event i occurred. $T^{(*)}$ refers to the total number of days in year y_i . However, the exact Julian day $t_i^{(*)}$ at which the event occurred was not always known for the compiled event histories. To account for the uncertainty in the dates of occurrence, a random sample of event dates uniformly distributed within a distinct period was therefore drawn. For events with yearly accuracy, we set the possible period of the event date from the beginning to the end of the year. For observations with monthly accuracy, the possible range of the event date was set accordingly to the beginning and end of the month.

The repose time r_i between event i and $i-1$ can then be calculated with

$$r_i = t_i^* - t_{i-1}^*, \quad (2)$$

based on the fractional years t_i^* and t_{i-1}^* . For dates with only interval information of event occurrence (yearly, monthly), the possible lower boundary of the repose time r_i^l as well as the upper boundary of the repose time r_i^u was calculated according to Equation (2).

If the time between debris-flow events follows a Poisson point process with events occurring continuously and independently at a

¹After Zimmermann et al. (1997) and Rickenmann (2016), respectively.

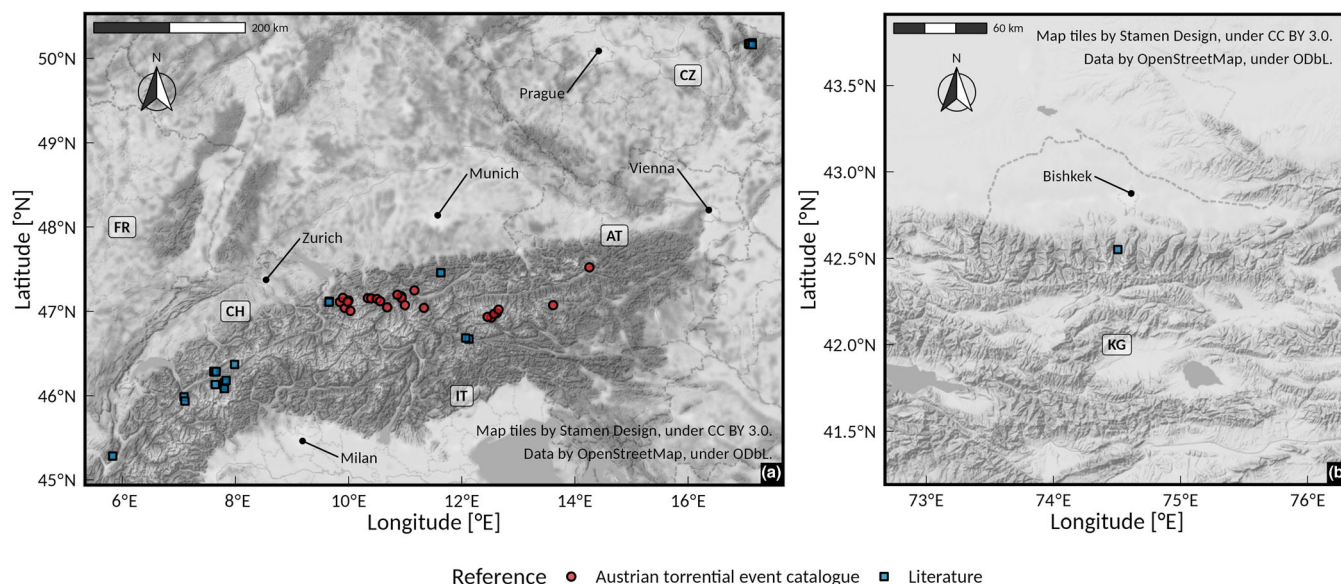


FIGURE 1 Location of catchments under consideration. A vast majority of catchments is located in Austria, Switzerland, Czechia, France and Italy (A). One catchment from the literature catalogue is located in Kyrgyzstan (B). [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/esp.5533)]

TABLE 1 Main characteristics of the debris-flow event series derived from literature. The location refers to the ISO-3166 code.^a The period given is the maximum available period, but only events from the year 1850 were used in the analysis. The 95% BCa confidence interval of the mean repose time was estimated based on 2500 bootstrap samples

Basin (location)	Observations	Period		Repose time in years			Study
		From	To	Mean	95% BCa-Cl		
Aksay (KG)	26	1877	2016	5.52	3.77	9.30	Zaginaev et al. (2016)
Bärenröfe (AT)	18	1839	2008	9.88	6.67	14.32	Procter et al. (2012)
Birchbach (CH)	52	1752	2001	4.86	3.81	6.27	Bollschweiler and Stoffel (2010)
Bruchji (CH)	43	1867	2002	3.19	2.75	3.75	Bollschweiler and Stoffel (2007)
Meng (AT)	31	1839	2008	5.60	3.84	8.10	Procter et al. (2011)
Entire Catchment (CZ)	24	1953	2013	2.57	1.91	3.96	Tichavský and Šilhán (2015)
Geistritzbach (CH)	14	1919	2003	6.38	4.14	9.29	Sorg et al. (2010)
Gratzentalbach (AT)	37	1800	2008	5.75	4.46	7.67	Mayer et al. (2010)
Grosse Grabe (CH)	51	1782	2001	4.36	3.35	6.16	Bollschweiler et al. (2008)
Illgraben (CH)	14	1965	2005	3.07	2.12	4.40	Arbellay et al. (2010)
Jelení Potok (CZ)	13	1953	2011	4.75	2.82	7.69	Tichavský et al. (2017)
Kaserbach (IT)	14	1741	1982	18.46	12.62	29.04	Strunk (1988)
Keprnická Potok (CZ)	13	1921	2011	7.42	4.30	14.18	Tichavský et al. (2017)
Klepáčský Potok (CZ)	20	1953	2011	3.00	1.95	4.89	Tichavský et al. (2017)
Manival (FR)	35	1889	2009	3.50	2.62	4.83	Lopez Saez et al. (2011)
Meretschbach (CH)	19	1940	2009	3.78	1.87	7.65	Szymczak et al. (2010)
Reuse de Saleinaz (CH)	40	1743	1995	6.44	4.51	10.26	Bollschweiler and Stoffel (2007)
Ritigraben (CH)	123	1570	2003	3.54	3.11	4.56	Stoffel et al. (2001)
Rudohorská Potok (CZ)	26	1921	2011	3.56	2.52	5.55	Tichavský et al. (2017)
Torrent de la Fouly (CH)	32	1862	1997	4.32	3.31	5.77	Bollschweiler and Stoffel (2007)
Torrent de Péterey (CH)	26	1861	2004	5.68	4.25	9.42	Stoffel and Bollschweiler (2009)
Wildbach (CH)	52	1623	2001	7.39	5.3	12.50	Schneuwly-Bollschweiler et al. (2013)
Wildsee area (IT)	12	1884	1990	9.55	7.91	11.07	Strunk (1988)

^aAT, Austria; CH, Switzerland; CZ, Czech Republic; FR, France; IT, Italy; KG, Kyrgyzstan.

constant average rate, repose times should be exponentially distributed. Hence we assume debris-flow event frequencies with irregular repose time patterns to follow an exponential distribution. Debris-

flow event frequencies showing regular or clustered repose time patterns indicate potential dependencies between events. We therefore tested the repose times of the compiled time series of all catchments

TABLE 2 Main characteristics of the debris-flow event series derived from the Austrian torrential event catalogue. The location refers to the ISO-3166 code of the Austrian federal states.^a The period given is the maximum available period, but only events from the year 1850 were used in the analysis. The 95% BCa confidence interval of the mean repose time was estimated based on 2500 bootstrap samples

Basin (location)	Observations	Period		Repose time in years		
		From	To	Mean	95% BCa-CI	
Acherbach (AT-7)	13	1838	2016	15	7.67	25.13
Enterbach (AT-7)	14	1808	2013	16	8.39	25.28
Farstrinne (AT-7)	41	1742	2016	7	4.89	10.05
Fendlermure (AT-7)	37	1773	2016	7	4.12	10.55
Fischbach (AT-7)	46	1340	2013	15	7.11	43.02
Gridlontobel (AT-7)	19	1789	2018	13	7.37	21.15
Gurnsbach (AT-7)	15	1922	2018	7	4.31	9.78
Hohe Riefe (AT-7)	13	1926	1986	5	2.4	9.56
Holzschmittbach (AT-7)	23	1929	2012	4	2.29	05.63
Hopfgartnergraben (AT-7)	13	1917	2016	8	4.18	14.09
Klausgraben (AT-5)	14	1878	1954	6	4.08	9.85
Lattenbach (AT-7)	33	1907	2018	3	2.24	5.22
Maurentobel (AT-8)	21	1929	2011	4	2.61	6.8
Mellitzbach 1 (AT-7)	11	1883	2012	13	5.55	31.71
Mellitzbach 2 (AT-7)	19	1882	2012	7	2.97	23.15
Muttentobel (AT-8)	11	1904	2016	11	5.13	25.09
Rotrütetobel (AT-8)	16	1870	1978	7	3.78	14.23
Sautnermure (AT-7)	18	1852	1984	8	3.65	16.74
Thialbach (AT-7)	29	1742	1981	8	5.78	13.7
Tröschnitzbach (AT-6)	17	1855	2011	10	6.63	13.11
Vensertobel (AT-8)	26	1893	2015	5	2.98	8.47
Winklertobel 1 (AT-8)	19	1855	1992	8	3.67	17.85
Winklertobel 2 (AT-8)	13	1919	1999	7	4.03	11.91
Wurgerbach (AT-7)	12	1882	2013	12	6.19	19.61
Unnamed Channel (AT-8)	16	1853	2003	10	5.43	19.55

^aAT-5, Salzburg; AT-6, Styria; AT-7, Tyrol; AT-8, Vorarlberg.

TABLE 3 Distributions used to model the frequency of the repose times. $f(r)$ is the probability density function, $F(r)$ is the cumulative distribution function and $h(r)$ is the hazard function, defined as $f(r)[1 - F(r)]^{-1}$. Note that for exponentially distributed repose times the hazard—that is, the instantaneous likelihood of event occurrence if no event occurred so far—is constant and therefore independent from the elapsed time since the last event, while for the Weibull and log-logistic the hazard depends on the time since the last event

Type	Density $f(r)$	Cumulative probability $F(r)$	Hazard $h(r)$
Exponential	$\theta \exp(-\theta r)$	$1 - \exp(-\theta r)$	θ
Weibull	$\theta_1 \theta_2^{-1} (r \theta_2^{-1})^{\theta_1 - 1} \exp(-(r \theta_2^{-1})^{\theta_1})$	$1 - \exp(-(r \theta_2^{-1})^{\theta_1})$	$\theta_1 \theta_2^{-1} (r \theta_2^{-1})^{\theta_1 - 1}$
Log-logistic	$\theta_1 r^{\theta_1 - 1} \theta_2^{-\theta_1} (1 + (r \theta_2^{-1})^{\theta_1})^{-2}$	$(1 + (r \theta_2^{-1})^{\theta_1})^{-1}$	$\theta_1 r^{\theta_1 - 1} \theta_2^{-\theta_1} (1 + (r \theta_2^{-1})^{\theta_1})^{-1}$

with respect to a Weibull as well as a log-logistic distribution. These heavy-tailed distributions are commonly used in survival analysis. Thus, we hypothesize that the repose time patterns of debris-flow events can be approximated by one of three repose time models: exponential, Weibull, or log-logistic.

To describe the likelihood that a debris flow will occur at time r from the last debris-flow event, conditional on the information that no debris-flow event happened before time r , we used the specific hazard function of the considered repose time models, defined according to

$$h(r) = \frac{f(r)}{S(r)}. \quad (3)$$

In Equation (3), $f(r)$ refers to the probability density function and $S(r)$ to the complementary distribution function $1 - F(r)$, with $F(r)$ denoting the cumulative distribution function of the considered repose time model. From Table 3 it can be seen that the hazard function for the case of exponentially distributed repose times is constant and consequently does not depend on previous debris-flow events. In contrast, the hazard functions of the Weibull and log-logistic

distributions are a function of the time since the last debris-flow event, and able to model increasing, decreasing and complex shapes, depending on the values of their parameters. Specifically, note that the shape parameter θ_1 of the Weibull distribution provides the flexibility to model both regular and clustered patterns. While $\theta_1 < 0$ indicates that the event rate decreases with time, $\theta_1 > 0$ signifies that the event rate increases over time. In the case of $\theta_1 = 0$, the Weibull distribution reduces to an exponential distribution, with the event rate being constant over time.

The parameters of the exponential, Weibull and log-logistic distribution were estimated by maximizing the likelihood, which can naturally incorporate information of censored observations:

$$L(\theta) = \prod_{i \in n} f(r_i|\theta) \prod_{i \in n_{lr}} [F(r_i^l|\theta) - F(r_i^u|\theta)] \prod_{i \in n_l} F(r_i^u|\theta) \prod_{i \in n_r} 1 - F(r_i^l|\theta). \quad (4)$$

In Equation (4), $L(\theta)$ is the likelihood function, θ is the parameter vector, f is the density function, F is the cumulative distribution function, r_i is the uncensored repose time, r_i^l is the lower and r_i^u the upper boundary of the censored repose time, n is the number of uncensored, n_{lr} is the number of interval-censored, n_l left-censored and n_r the number of right-censored repose times. The definition and parametrization of the distributions used are given in Table 3.

The general suitability of the distributions was tested based on a Monte Carlo version of the Kolmogorov-Smirnov test (Papale, 2018), estimated with

$$p = \frac{1}{n} \sum_{i=1}^n i \in \left\{ \max|\widehat{S}_i^*(r) - S(r)| \geq \max|\hat{S}(r) - S(r)| \right\}, \quad (5)$$

where p is the exceedance probability of the hypothesis that the repose times are drawn from the tested functions, n is the number of the Monte Carlo samples (set to 1000), and $\widehat{S}_i^*(r)$ the empirical survival function of the chosen distribution and the empirical survival function of the tested event history $\hat{S}(r)$. We estimated $\widehat{S}_i^*(r)$ based on a random sample of the same size as the tested debris-flow event series with the parameters resulting from maximizing Equation (3). The survival function of the repose times $\hat{S}(r)$ was estimated according to Wang and Taylor (2013). All tested distributions yielding a p -value larger than 0.05 were considered suitable.

To estimate the best-suited distribution among all suitable distributions, the Akaike information criterion (AIC) was utilized (Burnham & Anderson, 2002), where the distribution with the lowest AIC was chosen as the best fit.

The maximum likelihood estimation and the derivation of the AIC were performed using the R package `fitdistrplus` (Delignette-Muller & Dutang, 2015), while the estimation of empirical survival functions was performed using the R package `npsurv` (Wang, 2020).

4 | RESULTS

Resulting distributions and corresponding repose time patterns provide insight into the frequency characteristics of the catchments under consideration and support the assumption of three different repose time patterns (irregular, clustered and regular) as proposed by Zimmermann et al. (1997). This is evident from the goodness of fit of the selected distributions of the selected distributions which characterize the underlying repose time models (see Appendix B for a detailed overview). The resulting characteristics of the best-fitting repose time model for each catchment are summarized in Table 4, along with the number of

available events as well as model parameter estimates and corresponding uncertainty estimates for each model parameter. The specified hazards functions of the best suited distributions for all catchments are illustrated in Figures C1–C4 in Appendix C.

For 41 out of the 47 catchments a distribution could be successfully fitted to the repose times, resulting in 20 exponential, 16 Weibull and 5 log-logistic distributed repose times (Figure 2A).

Half of the event histories—20 out of 41 catchments—were characterized by a constant hazard function (Figure 2B). Here, the conditional probability of the next event was always the same, no matter how many times had passed since the last event. This is, consequently, a realization of an *irregular* repose time pattern.

The second most abundant group, which prevailed in 13 out of 41 catchments, was characterized by a decreasing hazard function resulting from the Weibull distribution (Figure 2C). Here, the conditional probability of the next event was highest close to the last event and leveled out to a constant probability with time. We denote such event histories as a *clustered* repose time pattern.

A third group was characterized by *regular* repose time patterns, which emerged in two different manifestations. As a consequence of Weibull-distributed repose times, 3 out of 41 catchments showed an increasing hazard function (Figure 2D). In this case, the conditional probability of occurrence increased relatively slowly with time elapsed from the last event. Another 5 out of 41 catchments showed a complex hazard function, resulting from log-logistic-distributed repose times (Figure 2E). For such catchments, the probability of event occurrence reached a peak after a rapid increase close after the last event, and then leveled out again over time.

The estimated repose times exhibit considerable variability between the catchments, regardless of the data source. The individual event rates, estimated according to Mudelsee (2010), range from less than 0.1 up to 0.7 debris flows per year for catchments from both the Austrian torrential event catalogue (Figure A1) and the literature catalogue (A2). Supplementary information on debris-flow occurrence rates for all data sets is provided in Appendix A.

Additional information on repose time models is available in Appendix B. Reported model characteristics comprise the p -values derived according to Equation (5) (Table B1) and the AIC values (Table B2). Furthermore, all repose times and the resulting complementary distributions of the best-suited models are illustrated in Figure B1.

The global mean repose time of the literature catalogue is 5.76 years, with a standard error of ± 0.71 years. This is shorter than the global mean repose time estimated for the Austrian torrential event catalogue, which is 8.64 years, with a corresponding standard error of ± 0.73 years. Hence the literature catalogue is characterized by a higher event rate of 0.21 debris flows per year, whereas the catchments selected from the Austrian event catalogue have a mean event rate of 0.14 debris flows per year.

5 | DISCUSSION

It has been known for more than 30 years that the occurrence of debris flows depends not only on hydrological but also on geological and topographical factors. Kienholz (1995) described the general conditions for triggering a debris flow as an interplay between a particular stress (critical rainfall/runoff) that is required to exceed the threshold of the system defined by its basic and variable sediment availability. Thus, a nonlinear

TABLE 4 Resulting repose time models and corresponding repose time patterns. Errors for the model parameters θ_i are estimated as their standard deviation derived from 1000 bootstrap samples. Basins in *italics* are taken from the literature, and basins in normal type are taken from the Austrian torrential event catalogue

Basin	Model	Events	θ_1	θ_2	Pattern
Acherbach	Exponential	11	0.09 ± 0.04		Irregular
Aksay	Exponential	25	0.19 ± 0.05		Irregular
Bärenröfe	Exponential	16	0.11 ± 0.02		Irregular
Channels Meng River	Exponential	29	0.2 ± 0.05		Irregular
Enterbach	Exponential	11	0.08 ± 0.03		Irregular
Entire catchment	Exponential	23	0.43 ± 0.09		Irregular
Fendlermure	Exponential	18	0.12 ± 0.04		Irregular
Geisttrifzbach	Exponential	13	0.17 ± 0.04		Irregular
Grosse Grabe	Exponential	42	0.29 ± 0.04		Irregular
Gurnsbach	Exponential	14	0.15 ± 0.04		Irregular
Hopfgartnergraben	Exponential	12	0.13 ± 0.05		Irregular
Jelení Potok	Exponential	12	0.23 ± 0.07		Irregular
Kaserbach	Exponential	8	0.07 ± 0.02		Irregular
Maurentobel	Exponential	20	0.26 ± 0.07		Irregular
Muttentobel	Exponential	10	0.11 ± 0.05		Irregular
Reuse de Saleinaz	Exponential	33	0.27 ± 0.04		Irregular
Torrent de la Fouly	Exponential	31	0.24 ± 0.04		Irregular
Tröschnitzbach	Exponential	16	0.11 ± 0.02		Irregular
Unnamed Channel	Exponential	15	0.11 ± 0.04		Irregular
Winklertobel 2	Exponential	12	0.16 ± 0.05		Irregular
Wurgerbach	Exponential	11	0.09 ± 0.03		Irregular
Farstrinne	Weibull	32	0.81 ± 0.15	4.46 ± 1.1	Clustered
Gridlontobel	Weibull	15	0.66 ± 0.21	8.37 ± 3.52	Clustered
Hohe Riefe	Weibull	11	0.79 ± 0.25	4.75 ± 1.92	Clustered
Holzschmittbach	Weibull	22	0.76 ± 0.15	3.15 ± 0.99	Clustered
Klepácká Potok	Weibull	19	1.1 ± 0.39	2.86 ± 0.76	Clustered
Lattenbach	Weibull	32	0.89 ± 0.1	3.18 ± 0.7	Clustered
Mellitzbach 1	Weibull	10	0.79 ± 0.2	10.59 ± 5.06	Clustered
Mellitzbach 2	Weibull	18	0.63 ± 0.15	4.61 ± 2.05	Clustered
Meretschibach	Weibull	18	0.75 ± 0.13	3.08 ± 1.13	Clustered
Rotrüfetobel	Weibull	15	0.84 ± 0.2	6.25 ± 2.22	Clustered
Sautermure	Weibull	17	0.66 ± 0.12	5.37 ± 2.15	Clustered
Vensertobel	Weibull	24	0.78 ± 0.15	4.32 ± 1.27	Clustered
Winklertobel 1	Weibull	18	0.67 ± 0.15	5.27 ± 2.1	Clustered
Fischbach	Log-logistic	28	1.37 ± 0.27	2.78 ± 0.7	Regular
Illgraben	Weibull	13	1.63 ± 0.54	3.33 ± 0.68	Regular
Keprnická Potok	Log-logistic	12	2.31 ± 0.7	4.93 ± 1.3	Regular
Klausgraben	Log-logistic	13	3.41 ± 1.02	4.59 ± 0.75	Regular
Thialbach	Log-logistic	17	1.34 ± 0.27	3.44 ± 1.29	Regular
Torrent de Pétérey	Log-logistic	25	2.52 ± 0.48	4.25 ± 0.61	Regular
Wildibach	Weibull	32	1.41 ± 0.3	5.07 ± 0.75	Regular
Wildsee area	Weibull	11	4.66 ± 1.29	10.49 ± 0.78	Regular

relationship between the magnitude and the recurrence interval in at least some catchments cannot be theoretically excluded, which was, in the absence of quantitative evidence, first confirmed by Zimmermann et al. (1997), who identified different debris-flow repose time patterns. The debris-flow specific repose time patterns were later also discussed in Rickenmann (2016). Their suggestion, based on Swiss events, is nowadays widely accepted and forms the basis for numerous studies and assumptions on debris-flow hazard analysis (Berger et al., 2011; Corominas et al., 2014; Jakob et al., 2020; Morell et al., 2021). By comparing trigger types of the Swiss catchments proposed by Zimmermann et al. (1997) and Rickenmann (2016), we analyzed how well our quantitative approach supports their heuristic assessment. However, only three out of seven catchments could be used for comparison. Three catchments (*Ri di Foioi*,

Buochser Ribi, *Leimbach*) had to be dropped since they did not fulfill the prerequisite of exhibiting at least 10 debris-flow events after the end of the Little Ice Age in 1850. For one catchment (Nolla), none of the selected survival functions could be fitted successfully, with the Kolmogorov–Smirnov test indicating significant departure of the observations from all reference probability distributions (Figure 3). The remaining catchments are the *Dorfbach Randa* as well as *Ritigraben*, both in the Canton of Valais (VS), and the *Steinlouibach* in the Canton of Obwalden (Lungern, OW). Figure 4 visually compares trigger types proposed by Zimmermann et al. (1997) and Rickenmann (2016) (abbreviated as Z&R) and those estimated based on the hazard functions of the best-fitting repose time models according to the dynamic threshold concept (DTC) proposed in this study for the three remaining catchments.

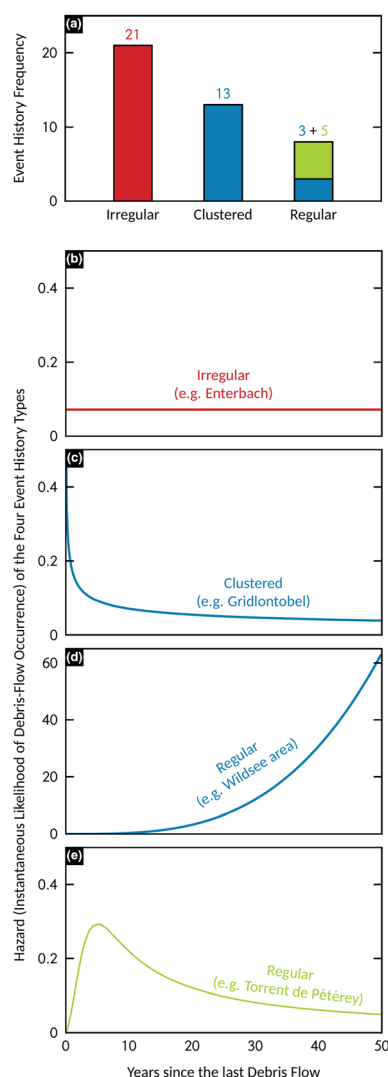


FIGURE 2 (A) Number of catchments with irregular (20), clustered (13) or regular (8) repose time patterns. In the case of regular patterns, the repose times in three catchments could be successfully modeled by a Weibull distribution, whereas in five catchments repose times of debris-flow events followed a log-logistic distribution. (B)–(E) Hazard functions exemplified for catchments showing either irregular (B: constant), clustered (C: decreasing) or regular (D: increasing and E: complex) debris-flow event repose times. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

The choice of trigger type in relation to the best-fit repose time model (DTC) is based on the distribution with the lowest AIC for all tested distributions (exponential, log-logistic and Weibull) whose p -value is greater than 0.05 (see Table 5).

The catchment of the Steinkloubach was identified by Zimmermann et al. (1997) and Rickenmann (2016) with a regular return period. Such a clear classification, however, is not conclusive—following the results of the best-fitting repose model concept. Based on the statistics, none of the trigger types can be excluded for this catchment. The trigger type DTC, given in Figure 4, is thus related to the distribution with the lowest AIC value (cf. Table 5). Zimmermann et al. (1997) and Rickenmann (2016) further classified the catchment of the Dorfbach Randa to be irregular in terms of debris-flow occurrence likelihood. However, according to the Monte Carlo version of the Kolmogorov–Smirnov test, the observed repose times at Dorfbach Randa are unlikely to be realizations drawn from an exponential distribution. Therefore, the assumption

of independence does not hold for events in this catchment. The best-fitting distribution (DTC) is given by the Weibull distribution. However, for the Ritigraben, the trigger types proposed by Zimmermann et al. (1997) and Rickenmann (2016) coincide with the best-fitting distribution (DTC), showing irregular and independence debris-flow repose times.

Although our results discussed here do not accurately reflect the heuristic assessment of Zimmermann et al. (1997) and Rickenmann (2016), it can be stated that we were able to quantify their fundamentally important classification of debris-flow repose time intervals that differed in size and spatial extent. However, as stated earlier, all events compiled for this study caused some form of damage and thus exceeded a critical magnitude. The influence of mitigation activities on the critical magnitude and thus on event series of debris flows derived from the literature can be considered negligible. However, based on the debris-flow event series derived from the Austrian torrential event catalogue, mitigation activity in recent decades could cause a shift in the critical magnitude or damage level, respectively. Analyses of debris-flow events based on the same torrential event catalogue showed no trend and the increase in mitigation activities was balanced by an increase in critical trigger conditions and exposed buildings in endangered areas (Schlögl et al., 2021). Thus, assuming stationarity of a critical threshold magnitude, we expect a comprehensive coverage of possible repose time patterns of debris-flow events for this study.

From this comprehensive collection of catchments, we found that an irregular (random) occurrence of events can be assumed for catchments with debris-flow events and repose periods that follow an exponential distribution. The most striking feature of such a repose type of debris-flow events is that their occurrence is independent and memoryless. This means that there is no mutual dependency between the events, and when referring to the total observation period there is no “overdue” event. Since the specific trigger disposition within such catchments is constant, the triggering of debris-flow events solely depends on critical runoff or precipitation, respectively, and a simple discrete Poisson distribution is likely to provide a reasonable fit and thus a solid basis for subsequent hazard assessment (Figure 5A).

However, our results also confirm the existence of non-exponentially distributed debris-flow repose times that can be differentiated into either regular or clustered occurrence patterns—reflected by increasing or decreasing hazard functions, respectively. For both types, debris-flow events in at least some of the catchments under consideration can no longer be considered to occur continuously and independently at a constant average rate.

In the case of regular debris-flow event intervals, the necessary disposition to trigger an event is affected by the antecedent event. In such catchments, the necessary sediment, immediately available after the previous event, is not available in a necessary quantity and a further debris flow can theoretically only be triggered by a runoff greater than the specific critical runoff. Hence the specific trigger disposition will only be reached after a certain amount of time has passed (Figure 5B).

Catchments with a decreasing hazard function exhibit clusters of debris-flow events for a certain period before the probability of occurrence for additional events levels out to the specific trigger disposition again. Because of higher sediment availability close after the event, the necessary critical runoff can be lower compared to the specific critical runoff (Figure 5C).

Our findings show that the incidence of debris-flow events is not always random, which would imply that their occurrence solely depends on critical precipitation events—supposing constant unlimited

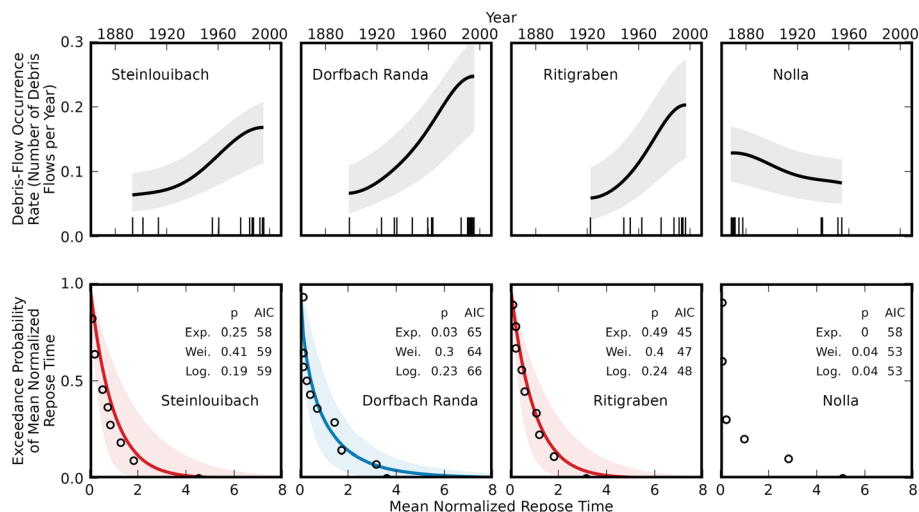


FIGURE 3 Estimated yearly debris-flow occurrence rate (top row) and corresponding estimated repose time distributions (bottom row) for the catchments investigated by Zimmermann *et al.* (1997) and Rickenmann (2016). The occurrence rate has been estimated according to the kernel approach by Mudelsee (2010). The corresponding pointwise 95% confidence interval is based on 1000 bootstrap samples. Documented events are shown as as rugs. All repose times were divided by their mean value to facilitate simultaneous visualization. The p -value refers to the Kolmogorov–Smirnov test for testing the principal suitability of the distribution (see Equation 5). The distribution with the lowest AIC value is shown with a pointwise 95% confidence interval based on 1000 bootstrap samples. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

FIGURE 4 Hazard functions for the three catchments investigated by Zimmermann *et al.* (1997) and Rickenmann (2016). “Z&R” denotes the trigger type according to Zimmermann and Rickenmann; “DTC” denotes the trigger type identified by the dynamic threshold concept described in this study. Note that the irregular repose time pattern for *Dorfbach Randa* would actually be discarded, since observed repose times are unlikely to be drawn from an exponential distribution. See Table 5 for details on the fitted distributions. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

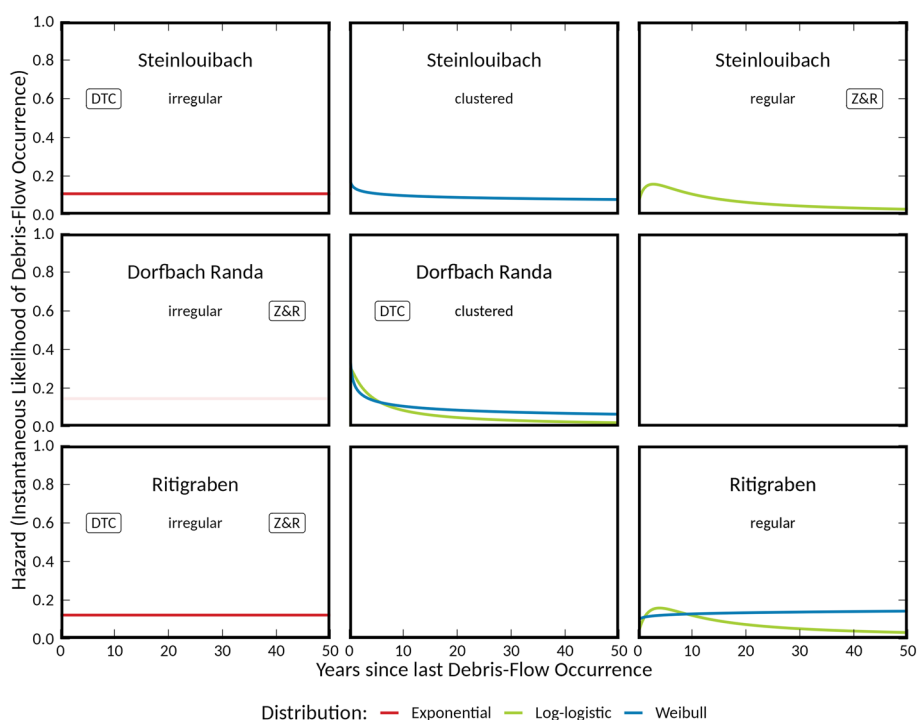


TABLE 5 Results for the events from Zimmermann *et al.* (1997) fulfilling defined prerequisites, where insignificant departure from the theoretical distribution defined as p -values greater or equal to 0.05, are shown in **bold**, while significant departure from the theoretical distribution is set in normal font. For each distribution, where the p -value was greater than 0.05, the minimum AIC, and therefore the best fit, is shown in **bold**

Basin	p -value			AIC		
	Log-logistic	Weibull	Exponential	Log-logistic	Weibull	Exponential
Steinlouibach (Lungern, OW)	0.191	0.414	0.247	59.22	59.33	57.76
Dorfbach Randa (BE)	0.235	0.298	0.031	66.18	64.43	64.76
Ritigraben (BE)	0.238	0.400	0.486	47.94	47.40	45.45

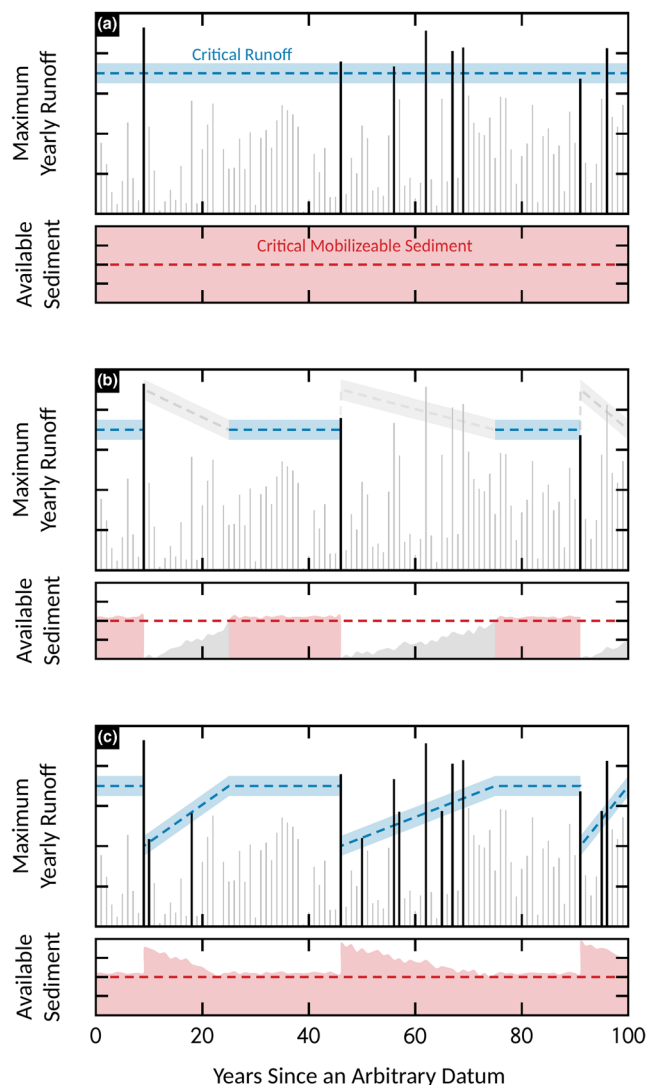


FIGURE 5 Dynamic threshold concept with respect to debris-flow initiation. Black bars are runoff events that triggered debris flows; grey bars are runoff events that did not trigger debris flows. (A) Irregular debris-flow occurrence is expected to be observed in catchments where neither the critical discharge nor the available sediment is altered by the last debris-flow event. Hence the catchment has no memory with regard to its event history. (B) Regular event occurrence is strongly related to the available, mobilizable sediment. After a debris-flow event, a substantial amount of sediment is removed and has to be accumulated again. In parallel, the critical discharge increases immediately after a debris-flow event, because of the more stable remaining sediment. It then decays again to pre-event conditions after a certain time period. (C) Clustering is expected to occur if a debris-flow event leads to instabilities in the catchment, which not only alter the available amount of mobilizable sediment but also lead to a decrease in the critical discharge. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

sediment supply. In some catchments, however, the occurrence of debris flows seems to be linked to a dynamic of the sediment availability as the main cause for the regular and clustered repose time intervals of debris-flow events. Rengers et al. (2020) found that frost weathering mechanisms are a key process for sedimentation in alpine catchments mainly exposed to bedrock. Their findings indicate that climate change might be directly linked to sediment channel refilling rates. However, sediment availability can also be affected by anthropogenic land use measures like ecosystem-based solutions for disaster risk reduction such as protective forests (Moos et al., 2018). This is an important aspect, as in many torrential catchments there is usually a relatively

large area designated to forest, for which the prevention of gravity-induced natural hazards is the most important control function (Brang et al., 2008; Scheidl et al., 2021). Sebal et al. (2019) showed that forest cover and forest patch density have a strong negative impact on the occurrence and frequency of damaging torrential events. Based on data from Austria, they found that a 25% increase in forest cover reduces the probability of damaging torrents by more than 8%, and numerous studies prove the mitigating impact of protective forests and its management by reducing the availability of sediments in torrential catchments (cf. Bischetti et al., 2016; Scheidl et al., 2020; Sidle, 2005). A direct impact in a catchment with a clustered occurrence of debris-flow events might, for instance, be caused by post-event logging to reduce the potential of large woody debris for future events—leading to unusually high erosion rates (due to root decay) and continued destabilization of local riparian areas (Comiti et al., 2006; Jochner et al., 2015; Mazzorana & Fuchs, 2010). Another direct effect on the triggering probability of debris flows can be seen in the increasing natural disturbances due to climate change, such as windthrow, bark beetle infestation or snow breakage, and the associated loss of the protective effect of forested land cover over a large area. Such a loss of protective effect is also particularly noticeable after wildfires (McGuire et al., 2021; Santi & Morandi, 2013). It is therefore conceivable that, in addition to the basic dispositional conditions of the catchment such as geology and relief energy, the management of protective forests may have a significant influence on debris-flow occurrence in alpine catchments.

However, as completeness of documented debris-flow events rarely exists, the applicability of our approach to classify different debris-flow repose time patterns is limited. Thus, future investigations at the level of individual catchment scale, identifying not only the basic disposition characteristics but also the potential effects of future land-cover management strategies in the focus of climate change and societal changes, are needed. Similar to Tierz et al. (2019), one strategy could be to find catchments that share enough common characteristics to be considered exchangeable to some extent.

6 | CONCLUSIONS

Analyzing potential debris-flow event frequencies in alpine catchments with regular or clustered event occurrences suggests ramifications with respect to probabilistic techniques used for torrential hazard assessments. From a long-term perspective, applying exponential distributions to model debris-flow event frequencies in such catchments will either result in an overestimation (for the case of regular repose types) or underestimation (for the case of clustered repose types) of the occurrence probability of an event. Consequently, these biased estimates entail potentially substantial implications for mitigation and adaptation as well as risk management. The observation that for some catchments triggering criteria cannot be considered independently and that, as a consequence, follow-up events might be dependent on previous events, may impact endeavors of risk communication with affected parties in the future.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available via PANGAEA at <https://doi.org/10.1594/PANGAEA.901061>. The code used for data preparation, processing, statistical analysis and graphical visualization of results is available on GitLab at <https://gitlab.com/Rexthor/repose-time-patterns>.

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APPENDIX A: OCCURRENCE RATES

The yearly debris-flow occurrence rate for each event series was estimated according to the method described in Mudelsee (2010, pp. 249–256) using a kernel approach:

$$\lambda(t) = h^{-1} \sum_{i=1}^n K\left(\frac{t - t_i^*}{h}\right), \quad (\text{A1})$$

where $\lambda(t)$ is the occurrence rate at time point t in debris flows per year, h is the bandwidth of the kernel estimated by cross-validation, K is the kernel function set to the Gaussian kernel $K(y) = (2\pi)^{-0.5} \exp(-y^2/2)$, and n is the total number of debris flows.

The resulting event series were corrected for boundary effects by generating pseudo-observation by means of reflecting the data to the left:

$$\hat{t}_i^* = t_1^* - (t_i^* - t_1^*), \quad (\text{A2})$$

and to the right:

$$\tilde{t}_i^* = t_n^* + (t_n^* - t_{n-i}^*), \quad (\text{A3})$$

until the event series approximately covered a period from $t_1^* - 3h$ to $t_n^* + 3h$. The resulting event series were used to estimate the occurrence rate according to Equation (A1). A fully bootstrapped approach based on 1000 iterations did not result in substantially different estimates when applied to sampling, pseudo-data generation and subsequent occurrence rate estimation. Therefore, the mean occurrence date was used, after pseudo-data generation, to estimate the occurrence rate. To account for uncertainties in the event series, the occurrence rate was calculated for 1000 bootstrap samples and the according 95% studentized confidence interval was estimated as suggested by Mudelsee (2010, algorithm 6.1, p. 255).

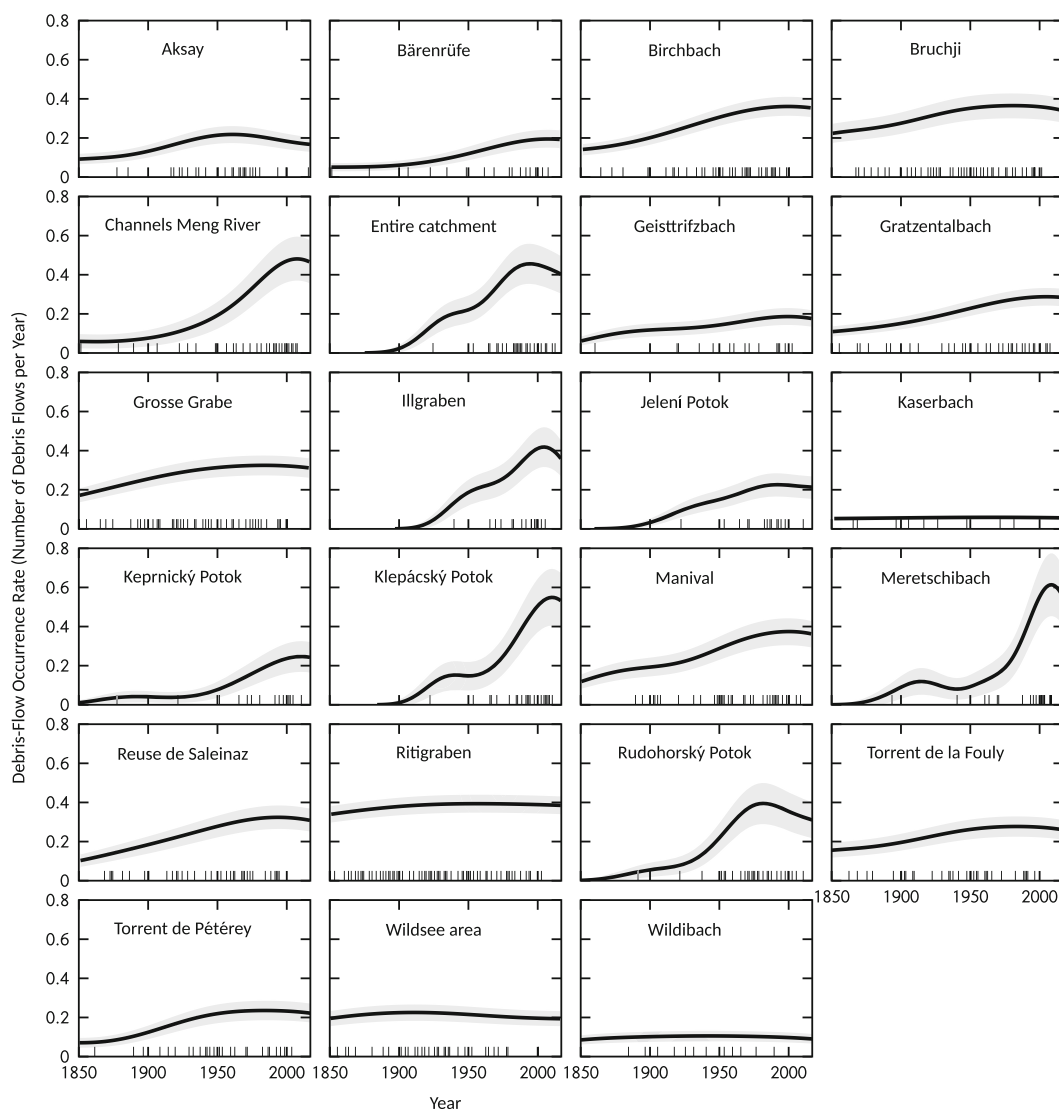


FIGURE A1 Estimated yearly debris-flow occurrence rate for the 23 catchments from the literature catalogue. The pointwise 95% confidence interval is based on 1000 bootstrap samples. The mean occurrence times of the observed debris flows are shown as thin black bars. Pseudo-events to account for boundary effects are shown as thin grey bars.

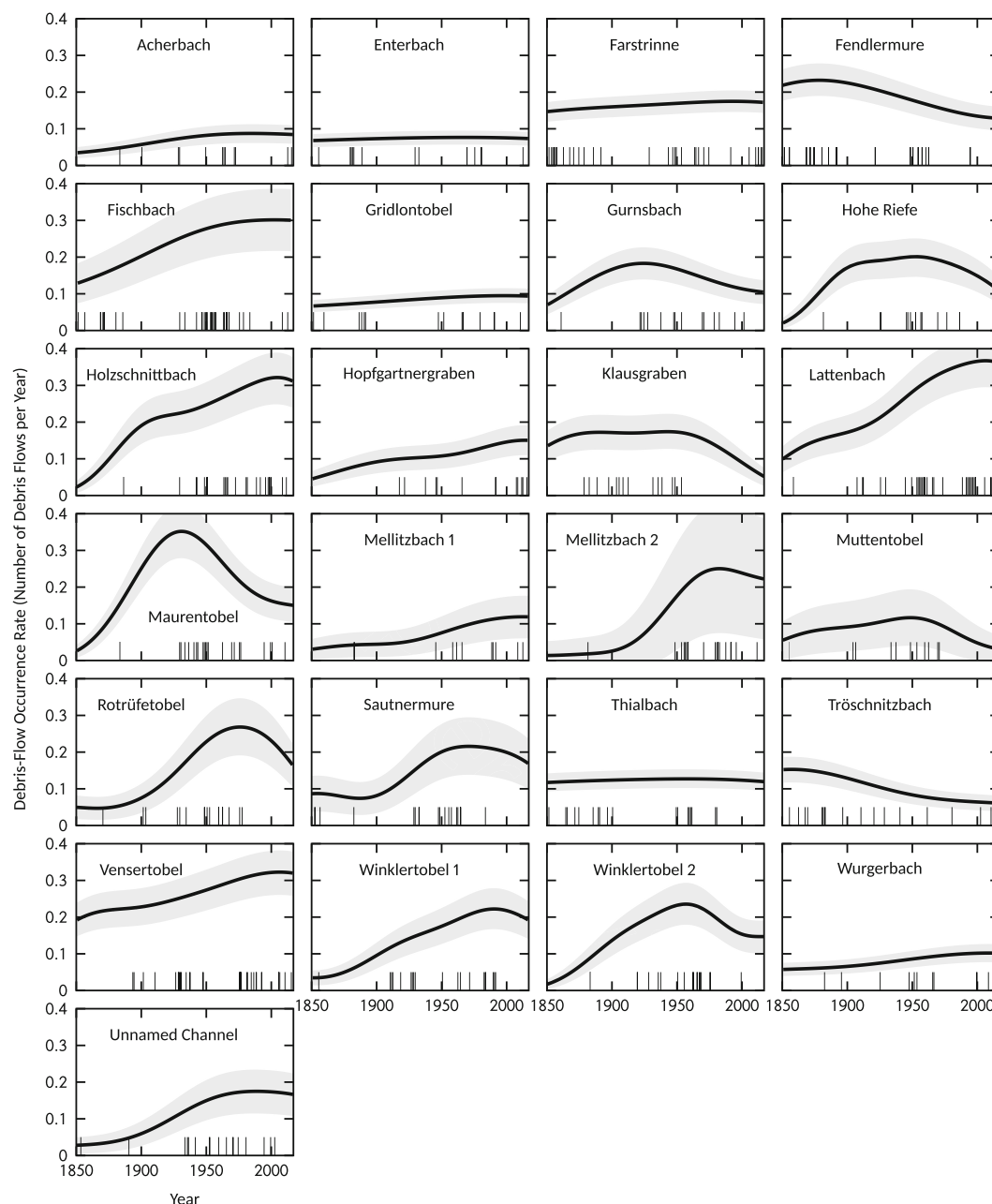


FIGURE A2 Estimated yearly debris-flow occurrence rate for the 25 catchments from the Austrian torrential event catalogue. The pointwise 95% confidence interval is based on 1000 bootstrap samples. The mean occurrence times of the observed debris flows are shown as thin black bars. Pseudo-events to account for boundary effects are shown as thin grey bars.

APPENDIX B: REPOSE TIME DISTRIBUTIONS

For each basin derived from the literature and the Austrian torrential event catalogue, the parameters of the exponential distribution, the Weibull distribution and the log-logistic distribution were estimated by maximizing the likelihood according to Equation (4), respecting the censored nature of the observations. The suitability of the distributions was estimated by the Kolmogorov–Smirnov statistics based on 1000 Monte Carlo samples according to Equation (5), using a non-parametric estimator of the empirical cumulative function for interval-censored data. The choice of a suitable candidate distribution was based on the minimum AIC value. The results of the procedure are

listed in Tables B1 and B2 for the literature catalogue and the Austrian torrential event catalogue, respectively.

The empirical survival function of the repose times was estimated as the complementary empirical cumulative distribution function. The variability, expressed as 95% pointwise confidence intervals, of the significant distributions with the lowest AIC value was estimated based on 1000 bootstrap samples. To enhance visualization, all repose times were divided by the respective mean. The resulting distributions, confidence regions and observations are illustrated in Figure B1 for the literature catalogue, and in Figure B2 for the Austrian torrential event catalogue, respectively.

TABLE B1 Results for the literature catalogue, where insignificant departure from the theoretical distribution, defined as p -values greater or equal to 0.05, are shown in **bold**, while significant departure from the theoretical distribution is set in normal font. For each distribution, where the p -value was greater than 0.05, the minimum AIC (i.e., the best fit) is shown in **bold**. For rows exhibiting only significant results, none of the three distributions was a plausible candidate

Basin	p -value			AIC		
	Log-logistic	Weibull	Exponential	Log-logistic	Weibull	Exponential
Aksay	0.03	0.16	0.16		106.0	104.0
Bärenröfe	0.11	0.18	0.60	92.0	90.9	90.4
Birchbach	0.00	0.00	0.00			
Bruchji	0.00	0.00	0.01			
Channels of the Meng	0.01	0.04	0.05			123.6
Entire catchment	0.00	0.05	0.23			58.4
Geisttrifzbach	0.30	0.28	0.30	62.0	59.4	58.1
Gratzentalbach	0.01	0.01	0.03			
Grosse Grabe	0.00	0.00	0.22			136.6
Illgraben	0.67	0.60	0.74	65.0	62.6	62.6
Jelení Potok	0.04	0.06	0.09		48.6	46.6
Kaserbach	0.35	0.38	0.71	49.1	49.5	48.7
Keprnická Potok	0.33	0.16	0.24	57.3	59.3	57.4
Klepáčský Potok	0.00	0.06	0.04		56.8	
Manival	0.00	0.00	0.01			
Meretschibach	0.90	0.75	0.08	143.2	143.1	145.6
Reuse de Saleinaz	0.00	0.07	0.09		126.7	124.8
Ritigraben	0.00	0.00	0.00			
Rudohorská Potok	0.01	0.01	0.04			
Torrent de la Fouly	0.00	0.01	0.09			111.4
Torrent de Pétérey	0.13	0.14	0.16	105.3	110.0	109.7
Wildibach	0.02	0.06	0.15		121.8	122.7
Wildsee area	0.28	0.18	0.14	43.2	41.3	58.4

TABLE B2 Results for the Austrian torrential event catalogue, where insignificant departure from the theoretical distribution defined as p -values greater or equal to 0.05, are shown in **bold**, while significant departure from the theoretical distribution is set in normal font. For each distribution, where the p -value was greater than 0.05, the minimum AIC (i.e., the best fit) is shown in **bold**

Basin	p -value			AIC		
	Log-logistic	Weibull	Exponential	Log-logistic	Weibull	Exponential
Acherbach	0.35	0.39	0.16	77.2	75.6	74.5
Enterbach	0.33	0.50	0.15	80.6	79.0	78.4
Farstrinne	0.43	0.71	0.35	167.0	162.6	165.0
Fendlermure	0.42	0.42	0.12	129.8	127.5	127.1
Fischbach	0.92	0.71	0.29	145.1	145.8	147.6
Gridlontobel	0.80	0.79	0.12	97.6	93.1	98.6
Gurnsbach	0.76	0.75	0.96	99.5	96.8	95.8
Hohe Riefe	0.78	0.81	0.58	64.4	61.5	61.6
Holzschmittbach	0.56	0.65	0.26	116.4	110.9	112.5
Hopfgartnergraben	0.92	0.52	0.19	91.7	89.6	88.6
Klausgraben	0.14	0.17	0.48	50.6	54.2	55.5
Lattenbach	0.33	0.12	0.02	145.3	145	
Maurentobel	0.04	0.14	0.09		92.5	90.6
Mellitzbach 1	0.87	0.54	0.08	70.5	69.8	70.5
Mellitzbach 2	0.48	0.67	0.00	121.3	120.6	
Muttentobel	0.80	0.46	0.39	70.3	72.1	70.2
Rotrütobel	0.44	0.73	0.21	100	98.2	98.2
Sautnermure	0.58	0.23	0.00	93.9	93.4	
Thialbach	0.22	0.48	0.08	85.5	85.7	86.9
Tröschnitzbach	0.32	0.35	0.64	97.2	92.3	91.2
Vensertobel	0.74	0.95	0.24	153.1	147.9	150.2
Winklertobel 1	0.28	0.15	0.00	97.9	97.0	
Winklertobel 2	0.89	0.84	0.86	77.6	75.6	73.6
Wurgerbach	0.62	0.98	0.68	79.6	75.9	75.3
Unnamed Channel	0.39	0.50	0.26	102	100.2	99.4

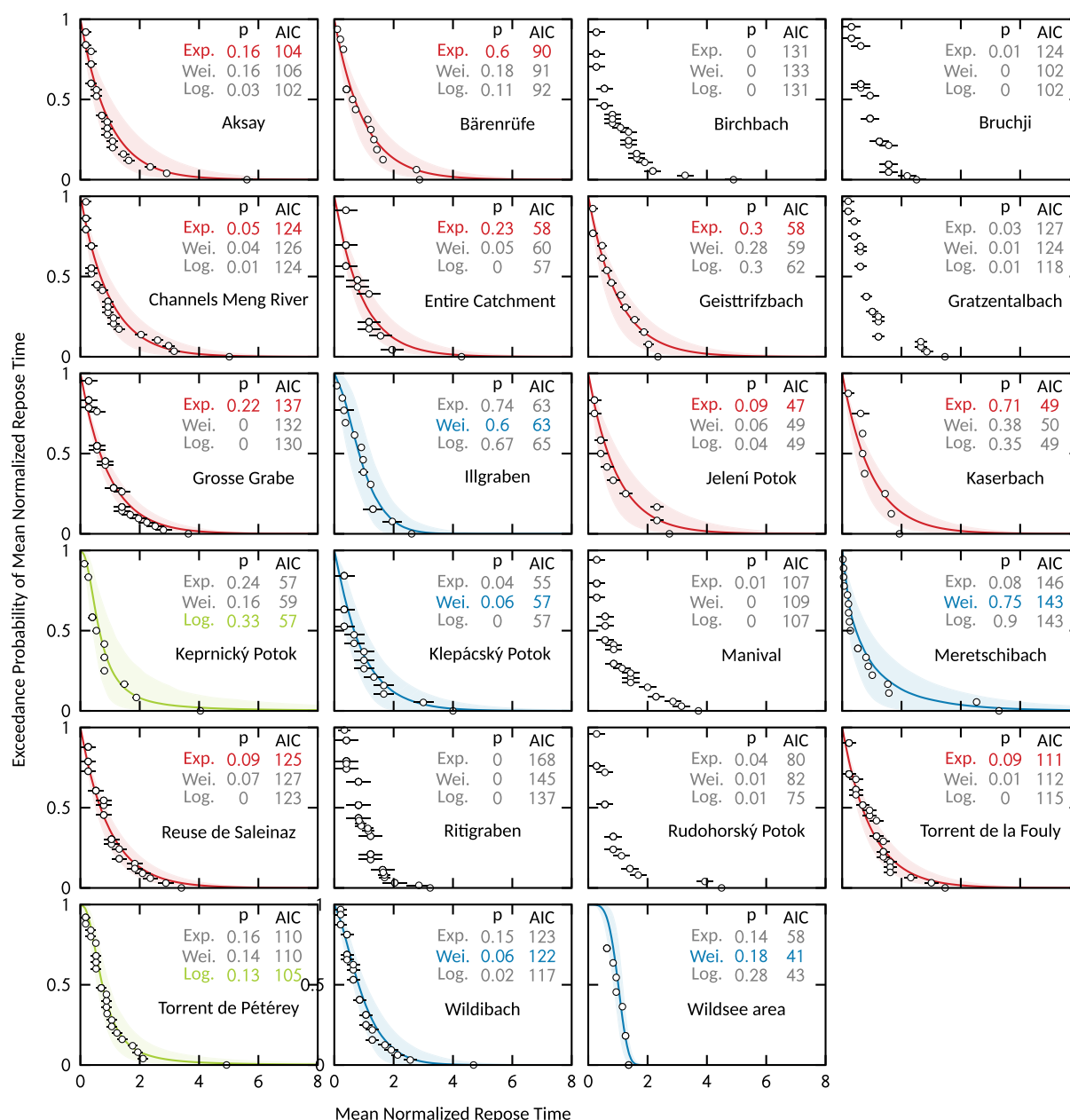


FIGURE B1 Estimated repose time distributions for the 23 catchments from the literature catalogue. Horizontal bars refer to the dating uncertainty. All repose times were divided by their mean value to enhance simultaneous visualization. The p -value refers to the Kolmogorov–Smirnov test for testing the principal suitability of the distribution (see Equation 5). The distribution with the lowest AIC value is shown with a pointwise 95% confidence interval based on 1000 bootstrap samples. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/terms-and-conditions)]

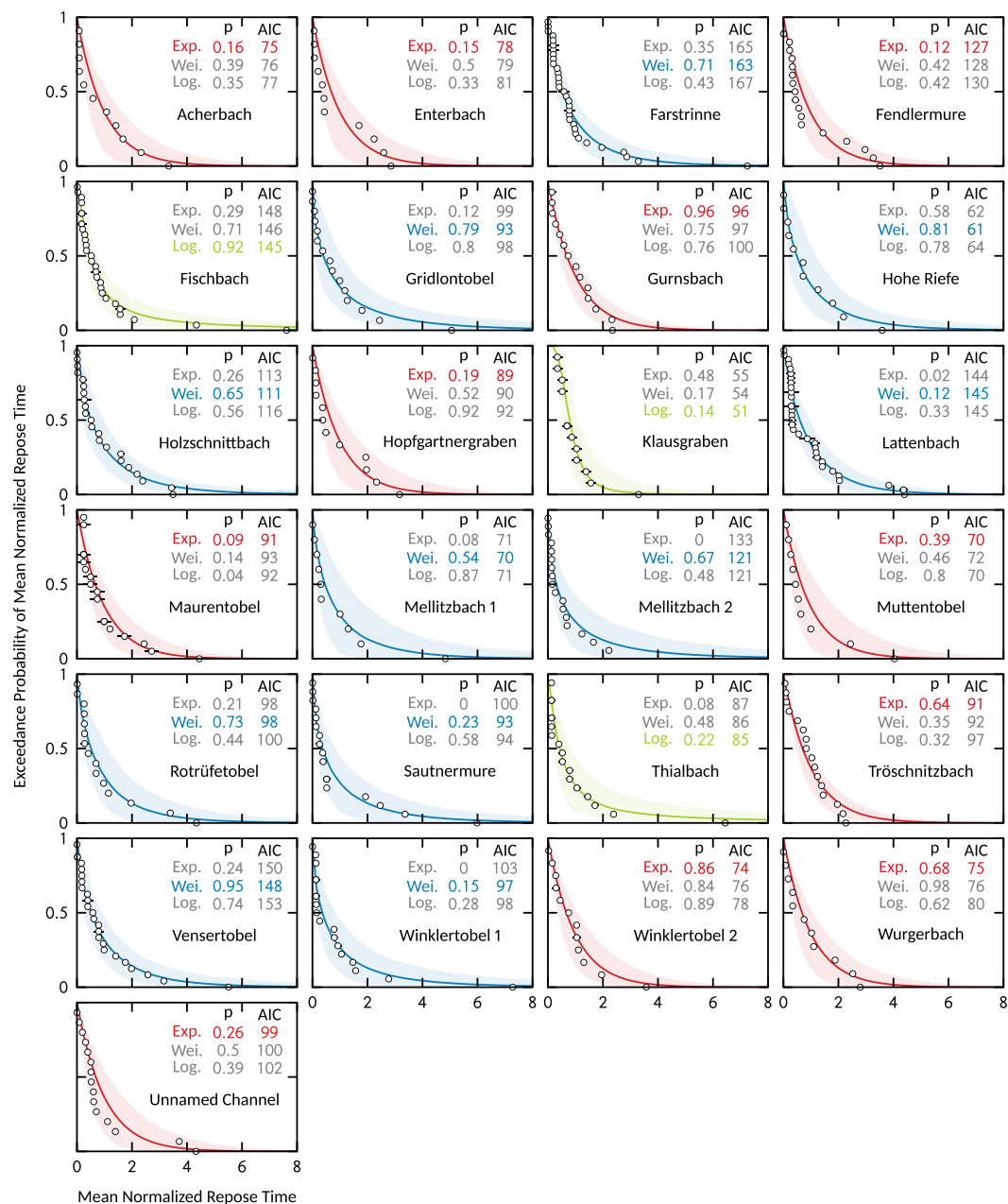


FIGURE B2 Estimated repose time distribution for the 25 catchments from the Austrian torrential event catalogue. Horizontal bars refer to the dating uncertainty. All repose times were divided by their mean value to enhance simultaneous visualization. The p -value refers to the Kolmogorov–Smirnov test for testing the principal suitability of the distribution (see Equation 5). The distribution with the lowest AIC value is shown with a pointwise 95% confidence interval based on 1000 bootstrap samples. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/esp.5533)]

APPENDIX C: SPECIFIC HAZARD FUNCTIONS

The hazard function was estimated as

$$h(r) = \frac{f(r)}{1 - F(r)}, \quad (C1)$$

where $f(r)$ is the probability density function and $F(r)$ is the cumulative probability function of the candidate distribution with the lowest

AIC value. $f(r)$ and $F(r)$ are defined according to Table 3, and their parameter values were estimated by maximum likelihood as defined in Equation (4).

The resulting hazard functions, with a 95% pointwise confidence interval based on 1000 bootstrap samples, for repose times up to 50 years and grouped per type, are shown in Figure C1 for exponentially distributed repose times, in Figures C2 and C3 for Weibull distributed repose times, and in Figure C4 for log-logistic distributed repose times.

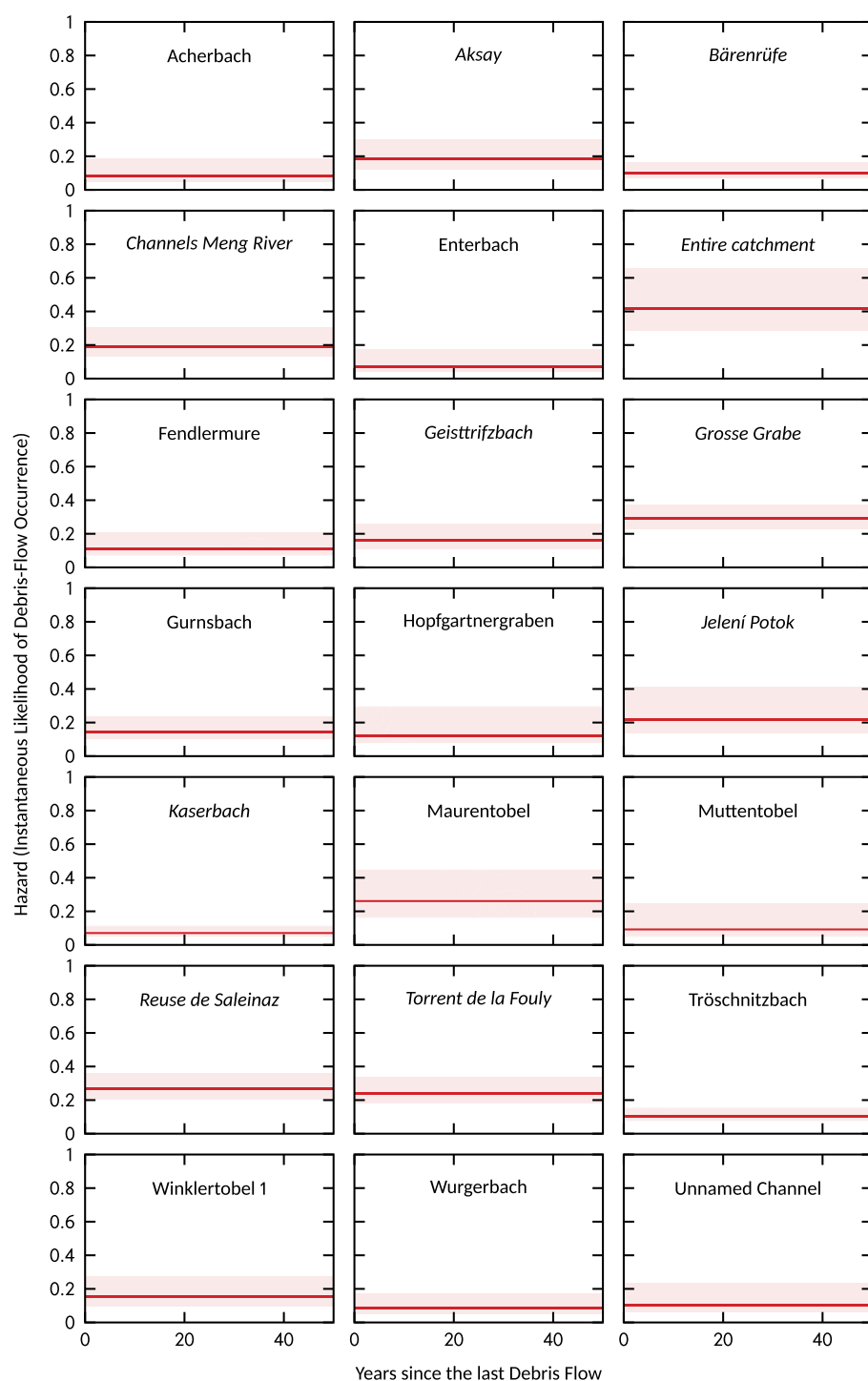


FIGURE C1 Hazard function for catchments with exponentially distributed repose times. Catchments from the literature catalogue are shown in *italics*, while catchments from the Austrian torrential event catalogue are shown in normal font. The pointwise 95% confidence interval, shown as shaded region, is based on 1000 bootstrap samples. [Color figure can be viewed at wileyonlinelibrary.com]

FIGURE C2 Hazard function for catchments with Weibull distributed repose times. Catchments from the literature catalogue are shown in *italics*, while catchments from the Austrian torrential event catalogue are shown in normal font. The pointwise 95% confidence interval, shown as shaded region, is based on 1000 bootstrap samples. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

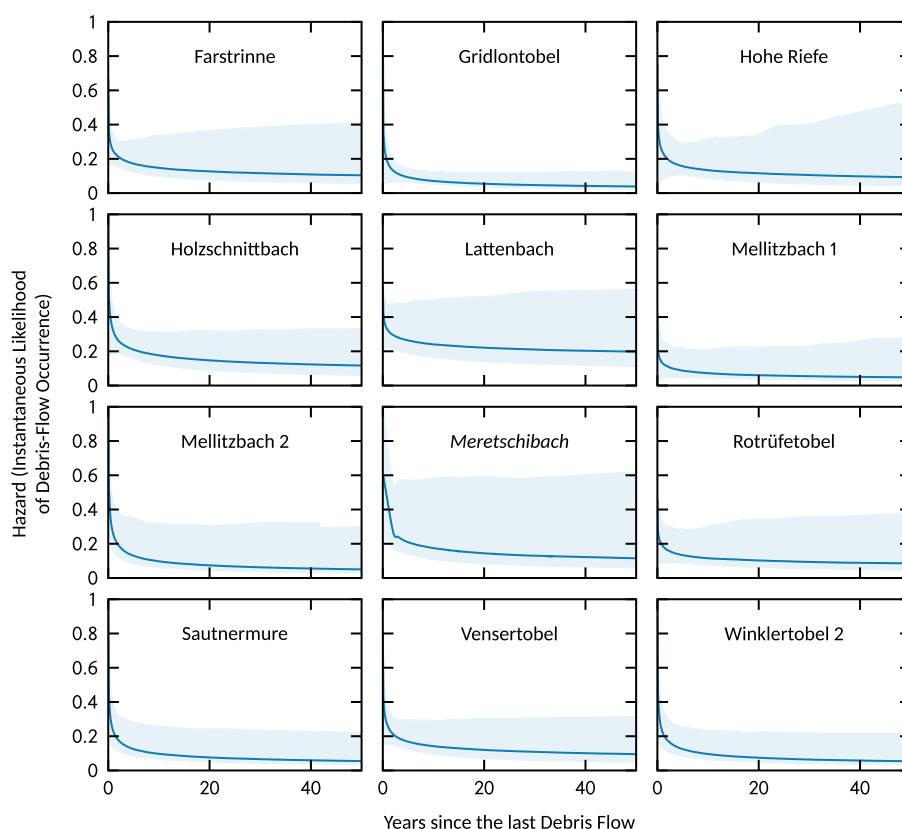


FIGURE C3 Hazard function for catchments with Weibull distributed repose times. Catchments from the literature catalogue are shown in *italics*, while catchments from the Austrian torrential event catalogue are shown in normal font. These catchments are shown separately because the bootstrap sample did not yield a meaningful confidence interval. Furthermore, the values of the hazard function are remarkably larger than in most other catchments. Note the different y-scaling for the second row. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

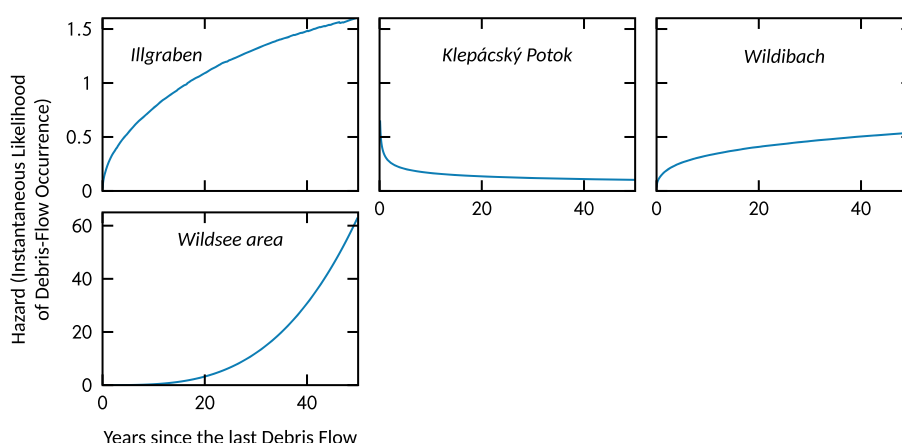


FIGURE C4 Hazard function for catchments with log-logistic distributed repose times. Catchments from the literature catalogue are shown in *italics*, while catchments from the Austrian torrential event catalogue are shown in normal font. The pointwise 95% confidence interval, shown as the shaded region, is based on 1000 bootstrap samples. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

