Supplementary Material

Beyond rainfall thresholds: hydrologic controls on debris-flow initiation in alpine channels

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Model equations

Table S1: Water balance, state and flux equations used in the hydrological model. Symbols shown in bold are model parameters. Subscripts u, h, g and f indicate the individual landscape units "unvegetated", 'high alpine vegetation', "grassland" and "forest", respectively. Model variables: P is total precipitation [mm hr^{-1}], P_S is solid precipitation (snow) [mm hr^{-1}], P_M is snow melt [mm hr^{-1}], P_R is rain [mm hr^{-1}], P_L is liquid precipitation [mm hr^{-1}], P_E is throughfall [mm hr^{-1}], E_P is potential evaporation [mm hr^{-1}], E_I is interception evaporation [mm hr^{-1}], R_F is preferential recharge [mm hr^{-1}], R_S is slow recharge [mm hr^{-1}], E_T is combined transpiration and soil evaporation [mm hr^{-1}], Q_S is flow from slow responding reservoir [mm hr^{-1}], Q_F is flow from the fast responding reservoir [mm hr^{-1}] and Q is the total flow [mm hr^{-1}]. Model parameters: $\mathbf{T_T}$ is the threshold temperature [°C], $\mathbf{F_M}$ is a melt factor [mm hr^{-1} °C^{-1}], $\mathbf{I_{max}}$ is the interception capacity [mm], $\mathbf{S_{U,max}}$ is the root-zone storage capacity [mm], $\boldsymbol{\gamma}$ is a shape factor [-], $\mathbf{L_p}$ is a vegetation water stress factor [-], **D** is a splitter [-], $\mathbf{k_S}$ is the storage coefficient of the slow responding reservoir [hr^{-1}], $\mathbf{k_F}$ is the storage coefficient for the fast responding riparian reservoir [hr^{-1}] and **A** is the areal fraction of each landscape unit [-].

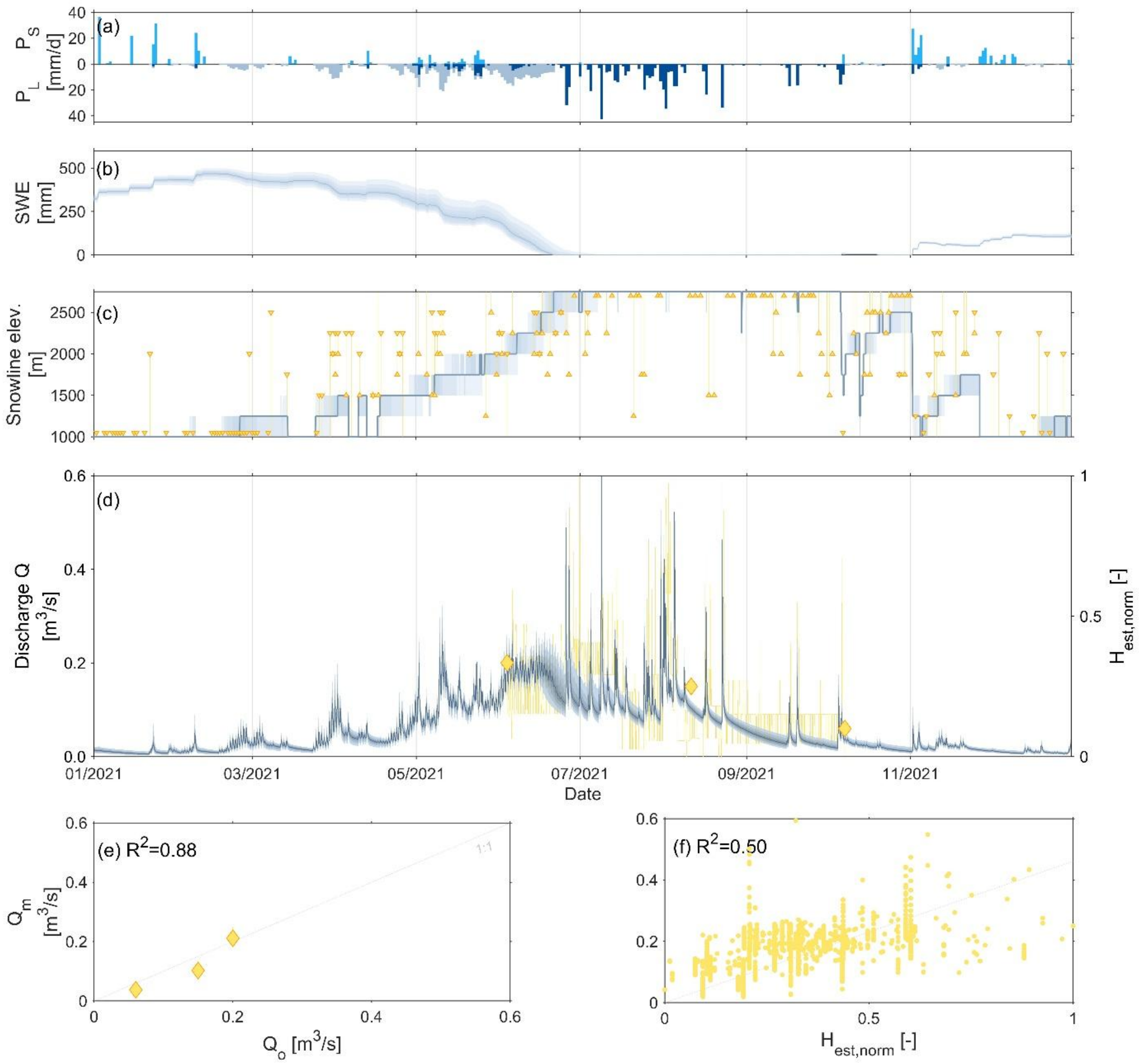
Landscape unit	Storage component	Water balance	Eq.	Constitutive equations	Eq.
Unvegetated	Snow storage	$dS_{snow,u}/dt = P_{S,u} - P_{M,u}$	(S1)	$P_{S,u} = \begin{cases} P, & T_u < \boldsymbol{T_T} \\ 0, & T_u \geq \boldsymbol{T_T} \end{cases}$	(S5)
	Unsaturated root-zone storage	$dS_{U,u}/dt = P_{E,u} - R_{F,u} - R_{S,u} - E_{T,u}$	(S2)	$P_{M,u} = \begin{cases} 0, & T_u < \boldsymbol{T_T} \\ min\left(\boldsymbol{F_M}(T_u - \boldsymbol{T_T}), \frac{S_{snow,u}}{dt}\right), & T_u \geq \boldsymbol{T_T} \end{cases}$	(S6)
	Fast responding storage	$dS_{F,u}/dt = R_{F,u} - Q_{F,u}$	(S3)	$P_{R,u} = \begin{cases} 0, & T_u < \boldsymbol{T_T} \\ P, & T_u \geq \boldsymbol{T_T} \end{cases}$	(S7)
	Slow responding storage	$dS_{S,u}/dt = R_{S,u} - Q_{S,u}$	(S4)	$P_{E,u} = P_{L,u} = P_{M,u} + P_{R,u}$	(S8)
				$C_{R,u} = 1 - \left(1 - \frac{S_{U,u}}{\boldsymbol{S_{U,max,u}}}\right)^{\boldsymbol{\gamma}}$	(S9)
				$E_{T,u} = E_P \frac{S_{U,u}}{\boldsymbol{S_{U,max,u}}} \frac{1}{\boldsymbol{L_P}}$	(S10)
				$R_{F,u} = \boldsymbol{D} C_{R,u} P_{E,u}$	(S11)
				$R_{S,u} = (1 - \boldsymbol{D}) C_{R,u} P_{E,u}$	(S12)
				$Q_{F,u} = S_{F,u} \boldsymbol{k_F}$	(S13)
				$Q_{S,u} = S_{S,u} \boldsymbol{k_S}$	(S14)
				$Q_u = Q_{F,u} + Q_{S,u}$	(S15)
High Alpine Vegetation	Snow storage	$dS_{snow,h}/dt = P_{S,h} - P_{M,h}$	(S16)	$P_{S,h} = \begin{cases} P, & T_h < \boldsymbol{T_T} \\ 0, & T_h \geq \boldsymbol{T_T} \end{cases}$	(S21)
	Interception storage	$dS_{I,h}/dt = P_{L,h} - P_{E,h} - E_{I,h}$	(S17)	$P_{M,h} = \begin{cases} 0, & T_h < \boldsymbol{T_T} \\ min\left(\boldsymbol{F_M}(T_h - \boldsymbol{T_T}), \frac{S_{snow,h}}{dt}\right), & T_h \geq \boldsymbol{T_T} \end{cases}$	(S22)
	Unsaturated root-zone storage	$dS_{U,h}/dt = P_{E,h} - R_{F,h} - R_{S,h} - E_{T,h}$	(S18)	$P_{R,h} = \begin{cases} 0, & T_h < \boldsymbol{T_T} \\ P, & T_h \geq \boldsymbol{T_T} \end{cases}$	(S23)
	Fast responding storage	$dS_{F,h}/dt = R_{F,h} - Q_{F,h}$	(S19)	$P_{L,h} = P_{M,h} + P_{R,h}$	(S24)
	Slow responding storage	$dS_{S,h}/dt = R_{S,h} - Q_{S,h}$	(S20)	$P_{E,h} = max\left(0, \frac{S_{I,h} - \boldsymbol{I_{max,h}}}{dt}\right)$	(S25)
				$E_{I,h} = min\left(E_P, \frac{S_{I,h} - P_{E,h}}{dt}\right)$	(S26)
				$C_{R,h} = 1 - \left(1 - \frac{S_{U,h}}{\boldsymbol{S_{U,max,h}}}\right)^{\boldsymbol{\gamma}}$	(S27)
				$E_{T,h} = E_P \frac{S_{U,h}}{\boldsymbol{S_{U,max,h}}} \frac{1}{\boldsymbol{L_P}}$	(S28)
				$R_{F,h} = \boldsymbol{D} C_{R,h} P_{E,h}$	(S29)
				$R_{S,h} = (1 - \boldsymbol{D}) C_{R,h} P_{E,h}$	(S30)
				$Q_{F,h} = S_{F,h} \boldsymbol{k_F}$	(S31)
				$Q_{S,h} = S_{S,h} \boldsymbol{k_S}$	(S32)
				$Q_h = Q_{F,h} + Q_{S,h}$	(S33)
Grassland	Snow storage	$dS_{snow,g}/dt = P_{S,g} - P_{M,g}$	(S34)	$P_{S,g} = \begin{cases} P, & T_g < \boldsymbol{T_T} \\ 0, & T_g \geq \boldsymbol{T_T} \end{cases}$	(S39)
	Interception storage	$dS_{I,g}/dt = P_{L,g} - P_{E,g} - E_{I,g}$	(S35)	$P_{M,g} = \begin{cases} 0, & T_g < \boldsymbol{T_T} \\ min\left(\boldsymbol{F_M}(T_g - \boldsymbol{T_T}), \frac{S_{snow,g}}{dt}\right), & T_g \geq \boldsymbol{T_T} \end{cases}$	(S40)
	Unsaturated root-zone storage	$dS_{U,g}/dt = P_{E,g} - R_{F,g} - R_{S,g} - E_{T,g}$	(S36)	$P_{R,g} = \begin{cases} 0, & T_g < \boldsymbol{T_T} \\ P, & T_g \geq \boldsymbol{T_T} \end{cases}$	(S41)
	Fast responding storage	$dS_{F,g}/dt = R_{F,g} - Q_{F,g}$	(S37)	$P_{L,g} = P_{M,g} + P_{R,g}$	(S42)
	Slow responding storage	$dS_{S,g}/dt = R_{S,g} - Q_{S,g}$	(S38)	$P_{E,g} = max\left(0, \frac{S_{I,g} - \boldsymbol{I_{max,g}}}{dt}\right)$	(S43)
				$E_{I,g} = min\left(E_P, \frac{S_{I,g} - P_{E,g}}{dt}\right)$	(S44)
				$C_{R,g} = 1 - \left(1 - \frac{S_{U,g}}{\boldsymbol{S_{U,max,g}}}\right)^{\boldsymbol{\gamma}}$	(S45)
				$E_{T,g} = E_P \frac{S_{U,g}}{\boldsymbol{S_{U,max,g}}} \frac{1}{\boldsymbol{L_P}}$	(S46)
				$R_{F,g} = \boldsymbol{D} C_{R,g} P_{E,g}$	(S47)
				$R_{S,g} = (1 - \boldsymbol{D}) C_{R,g} P_{E,g}$	(S48)
				$Q_{F,g} = S_{F,g} \boldsymbol{k_F}$	(S49)
				$Q_{S,g} = S_{S,g} \boldsymbol{k_S}$	(S50)
				$Q_g = Q_{F,g} + Q_{S,g}$	(S51)

Table S1 (continued)

Landscape unit	Storage component	Water balance	Eq.	Constitutive equations	Eq.
Forest	Snow storage	$dS_{snow,f}/dt = P_{S,f} - P_{M,f}$	(S52)	$P_{S,f} = \begin{cases} P, & T_f < \boldsymbol{T_T} \\ 0, & T_f \geq \boldsymbol{T_T} \end{cases}$	(S57)
	Interception storage	$dS_{I,f}/dt = P_{L,f} - P_{E,f} - E_{I,f}$	(S53)	$P_{M,f} = \begin{cases} 0, & T_f < \boldsymbol{T_T} \\ min\left(\boldsymbol{F_M}(T_f - \boldsymbol{T_T}), \frac{S_{snow,f}}{dt}\right), & T_f \geq \boldsymbol{T_T} \end{cases}$	(S58)
	Unsaturated root-zone storage	$dS_{U,f}/dt = P_{E,f} - R_{F,f} - R_{S,f} - E_{T,f}$	(S54)	$P_{R,f} = \begin{cases} 0, T_f < \boldsymbol{T_T} \\ P, \ T_f \geq \boldsymbol{T_T} \end{cases}$	(S59)
	Fast responding storage	$dS_{F,f}/dt = R_{F,f} - Q_{F,f}$	(S55)	$P_{L,f} = P_{M,f} + P_{R,f}$	(S60)
	Slow responding storage	$dS_{S,f}/dt = R_{S,f} - Q_{S,f}$	(S56)	$P_{E,f} = max\left(0, \frac{S_{I,f} - \boldsymbol{I_{max,f}}}{dt}\right)$	(S61)
				$E_{I,f} = min\left(E_P, \frac{S_{I,f} - P_{E,f}}{dt}\right)$	(S62)
				$C_{R,f} = 1 - \left(1 - \frac{S_{U,f}}{\boldsymbol{S_{U,max,f}}}\right)^{\boldsymbol{\gamma}}$	(S63)
				$E_{T,f} = E_P \frac{S_{U,f}}{\boldsymbol{S_{U,max,f}}} \frac{1}{\boldsymbol{L_P}}$	(S64)
				$R_{F,f} = \boldsymbol{D} C_{R,f} P_{E,f}$	(S65)
				$R_{S,f} = (1 - \boldsymbol{D}) C_{R,f} P_{E,f}$	(S66)
				$Q_{F,f} = S_{F,f} \boldsymbol{k_F}$	(S67)
				$Q_{S,f} = S_{S,f} \boldsymbol{k_S}$	(S68)
				$Q_f = Q_{F,f} + Q_{S,f}$	(S69)
				$Q = A_u Q_u + A_h Q_h + A_g Q_g + A_f Q_f$	(S70)

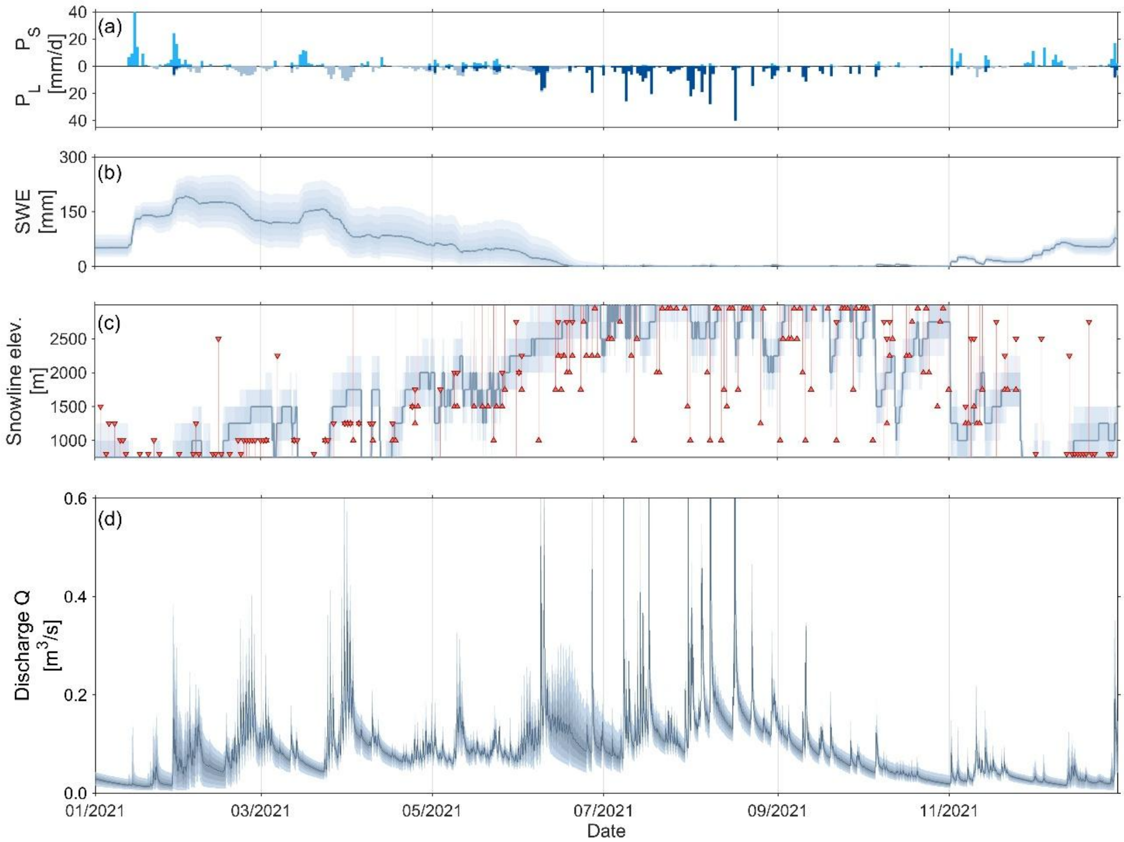
Model calibration ID1c - Hopfgartnergraben

Figure S1. Modelled and observed variables for the 2021 calibration period in ID1c – Hopfgartnergraben catchment. (a) modelled snowfall P_S (light blue) and liquid precipitation P_L, distinguishing snow melt (light grey-blue) and rainfall (dark blue), (b) modelled snow water equivalent SWE, (c) modelled (blue) and observed (orange triangles) snow line elevation E_{SL}. On days with full cloud cover no E_{SL} observation available. On days with partial cloud cover E_{SL} cannot be unambiguously determined and only its lower (upward pointing orange triangles) and/or upper limits (downward pointing orange triangles) are known. Only on days without cloud cover E_{SL} is unambiguously determined: when the catchment is partially snow covered the upward and downward pointing triangles coincide, when there is no snow cover the upward pointing triangles coincide with the highest elevation and when there is 100% snow cover, the downward pointing triangles coincide with the lowest elevation. (d) modelled (blue) and observed stream discharge Q (orange diamond symbols) as well as normalized observed water levels $H_{est,norm}$ (orange line), (e) observed vs. modelled stream discharge Q, with error bars indicating the 5/95th model uncertainty interval and (f) observed water levels $H_{est,norm}$ vs. modelled stream discharge Q. The dark blue lines in (b)-(d) indicate the median of all retained model solutions and the blue shaded areas the associated 5/95th uncertainty intervals.



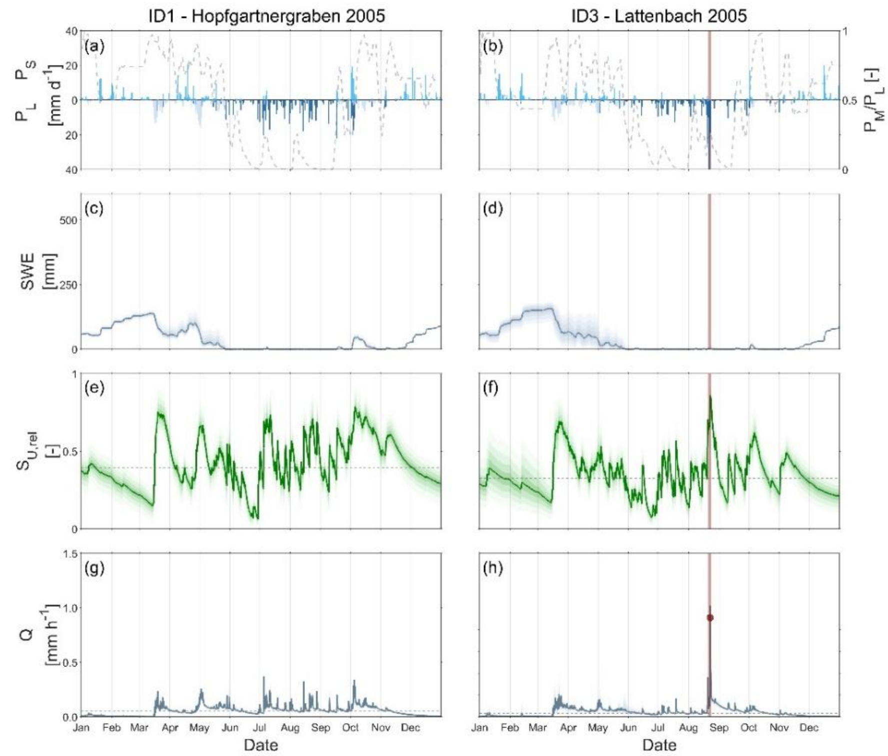
Model calibration ID3c - Lattenbach

Figure S2. Modelled and observed variables for the 2021 calibration period in ID3c – Lattenbach catchment. (a) modelled snowfall P_S (light blue) and liquid precipitation P_L, distinguishing snow melt (light grey-blue) and rainfall (dark blue), (b) modelled snow water equivalent SWE, (c) modelled (blue) and observed (dark red triangles) snow line elevation E_{SL}. On days with full cloud cover no E_{SL} observation available. On days with partial cloud cover E_{SL} cannot be unambiguously determined and only its lower (upward pointing dark red triangles) and/or upper limits (downward pointing dark red triangles) are known. Only on days without cloud cover E_{SL} is unambiguously determined: when the catchment is partially snow covered the upward and downward pointing triangles coincide, when there is no snow cover the upward pointing triangles coincide with the highest elevation and when there is 100% snow cover, the downward pointing triangles coincide with the lowest elevation. (d) modelled (blue) stream discharge Q.



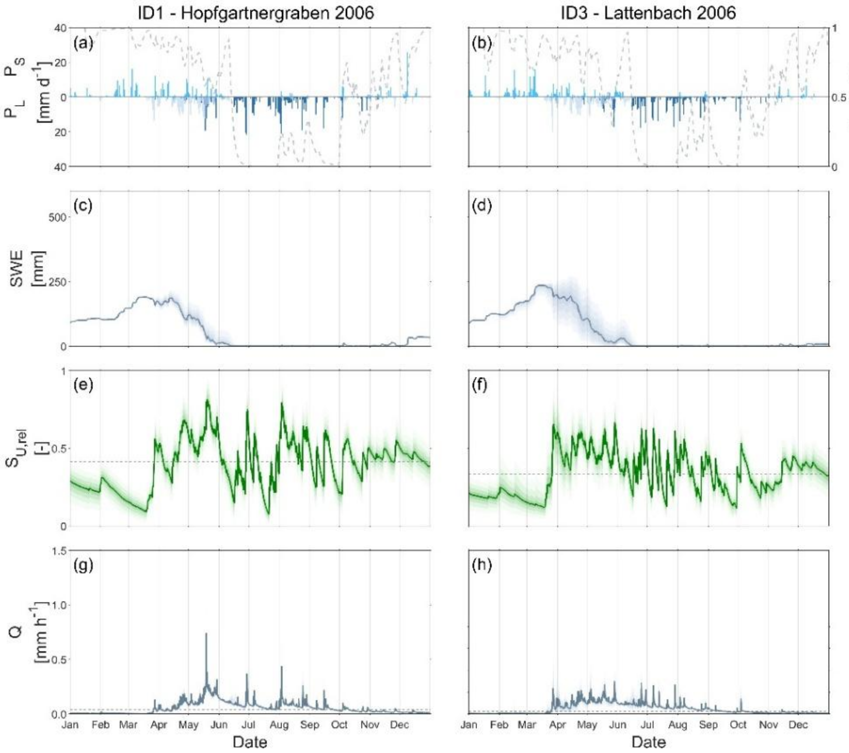
All catchments 2005

Figure S3. Hydrological variables of study catchments ID1 and ID3 for the year 2005. (a), (b) median modelled snowfall P_S (light blue) and liquid precipitation P_L, distinguishing snow melt (light grey-blue) and rainfall (dark blue), the dashed line indicates the fraction of snowmelt to the total liquid water input, i.e. P_M/P_L; (c), (d) median modelled snow water equivalent SWE (solid blue line) and the 5/95th uncertainty interval (blue shaded area); (e), (f) median modelled relative soil moisture S_U (solid green line), the 5/95th uncertainty interval (green shaded area) and the 2005 average S_U (dashed grey line); (g), (h) median modelled stream flow Q (solid blue line), the 5/95th uncertainty interval (blue shaded area) and the 2005 average Q (dashed grey lines). The dark red bar (ID3) indicates the date of observed debris flows and the circle symbol indicates the median modelled channel stream flow Q associated with each debris flow.



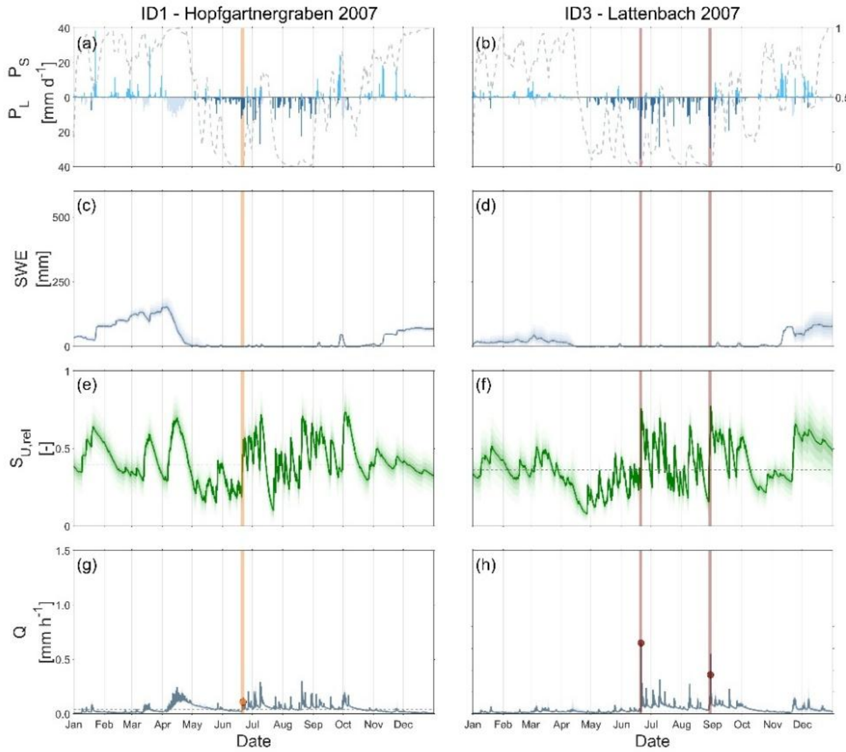
All catchments 2006

Figure S4. Hydrological variables of study catchments ID1 and ID3 for the year 2006. (a), (b) median modelled snowfall P_S (light blue) and liquid precipitation P_L, distinguishing snow melt (light grey-blue) and rainfall (dark blue), the dashed line indicates the fraction of snowmelt to the total liquid water input, i.e. P_M/P_L; (c), (d) median modelled snow water equivalent SWE (solid blue line) and the 5/95th uncertainty interval (blue shaded area); (e), (f) median modelled relative soil moisture S_U (solid green line), the 5/95th uncertainty interval (green shaded area) and the 2006 average S_U (dashed grey line); (g), (h) median modelled stream flow Q (solid blue line), the 5/95th uncertainty interval (blue shaded area) and the 2006 average Q (dashed grey lines).



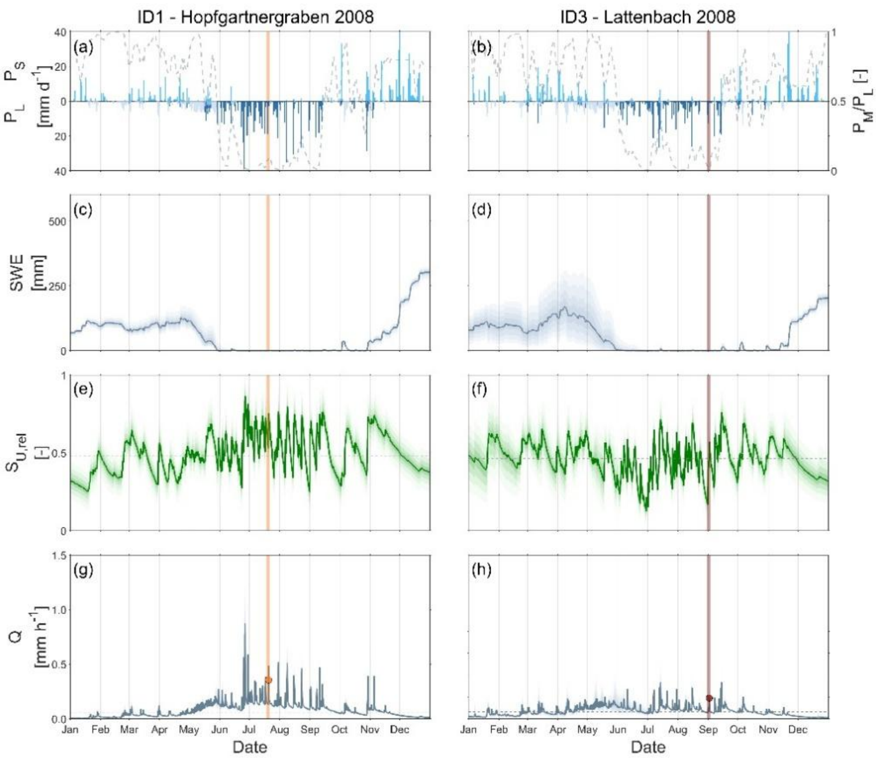
All catchments 2007

Figure S5. Hydrological variables of study catchments ID1 and ID3 for the year 2007. (a), (b) median modelled snowfall P_S (light blue) and liquid precipitation P_L, distinguishing snow melt (light grey-blue) and rainfall (dark blue), the dashed line indicates the fraction of snowmelt to the total liquid water input, i.e. P_M/P_L; (c), (d) median modelled snow water equivalent SWE (solid blue line) and the 5/95th uncertainty interval (blue shaded area); (e), (f) median modelled relative soil moisture S_U (solid green line), the 5/95th uncertainty interval (green shaded area) and the 2007 average S_U (dashed grey line); (g), (h) median modelled stream flow Q (solid blue line), the 5/95th uncertainty interval (blue shaded area) and the 2007 average Q (dashed grey lines). The orange (ID1) dark red bars (ID3) indicate the date of observed debris flows and the circle symbols indicate the median modelled channel stream flow Q associated with each debris flow.



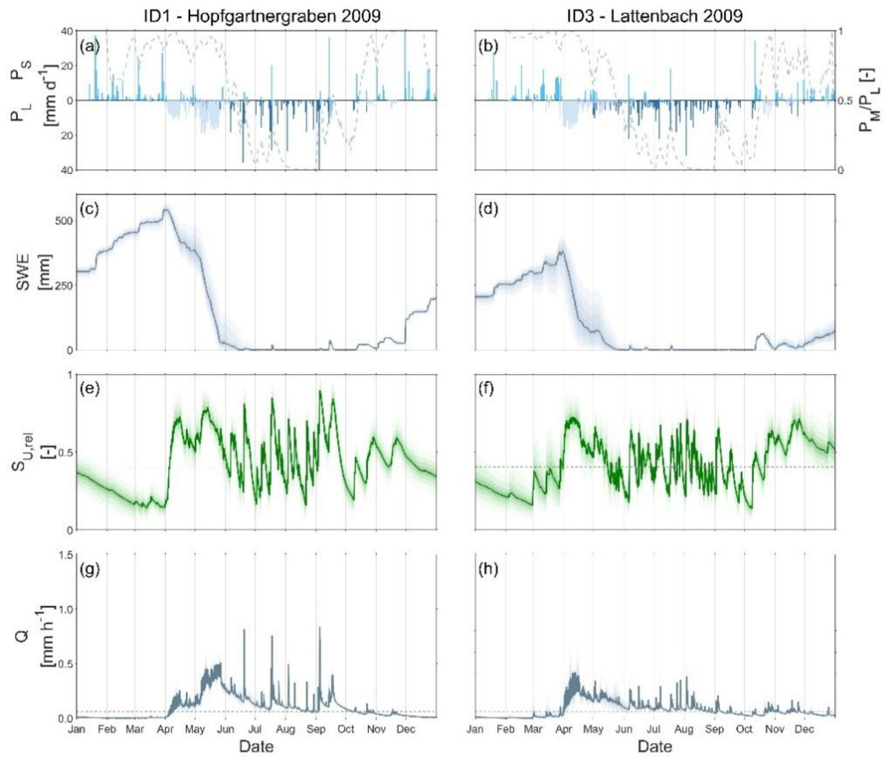
All catchments 2008

Figure S6. Hydrological variables of study catchments ID1 and ID3 for the year 2008. (a), (b) median modelled snowfall P_S (light blue) and liquid precipitation P_L, distinguishing snow melt (light grey-blue) and rainfall (dark blue), the dashed line indicates the fraction of snowmelt to the total liquid water input, i.e. P_M/P_L; (c), (d) median modelled snow water equivalent SWE (solid blue line) and the 5/95th uncertainty interval (blue shaded area); (e), (f) median modelled relative soil moisture S_U (solid green line), the 5/95th uncertainty interval (green shaded area) and the 2008 average S_U (dashed grey line); (g), (h) median modelled stream flow Q (solid blue line), the 5/95th uncertainty interval (blue shaded area) and the 2008 average Q (dashed grey lines). The orange (ID1) dark red bars (ID3) indicate the date of observed debris flows and the circle symbols indicate the median modelled channel stream flow Q associated with each debris flow.



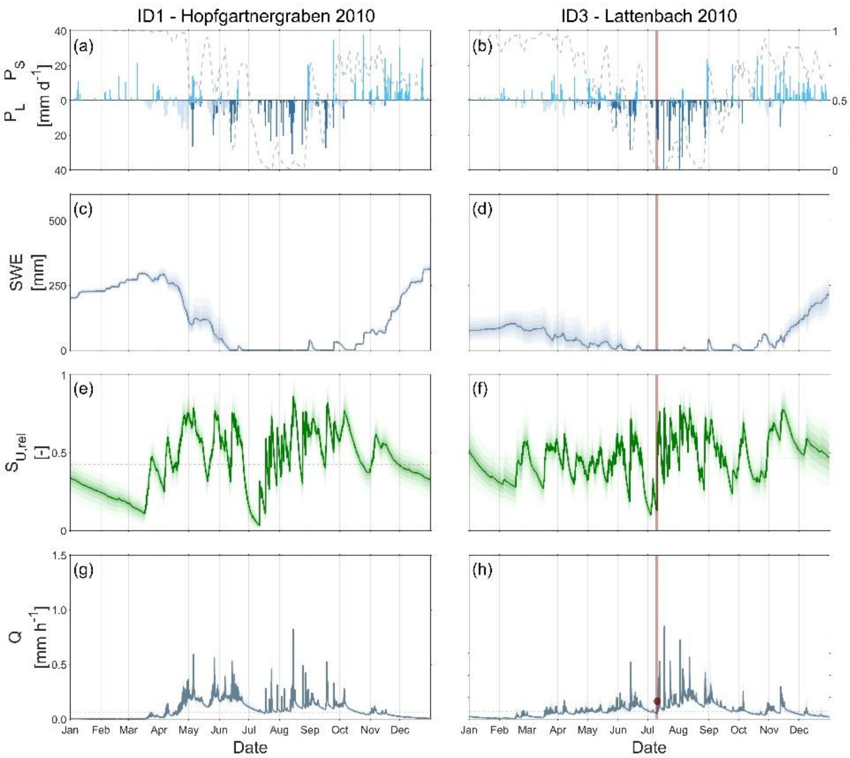
All catchments 2009

Figure S7. Hydrological variables of study catchments ID1 and ID3 for the year 2009. (a), (b) median modelled snowfall P_S (light blue) and liquid precipitation P_L, distinguishing snow melt (light grey-blue) and rainfall (dark blue), the dashed line indicates the fraction of snowmelt to the total liquid water input, i.e. P_M/P_L; (c), (d) median modelled snow water equivalent SWE (solid blue line) and the 5/95[th] uncertainty interval (blue shaded area); (e), (f) median modelled relative soil moisture S_U (solid green line), the 5/95[th] uncertainty interval (green shaded area) and the 2009 average S_U (dashed grey line); (g), (h) median modelled stream flow Q (solid blue line), the 5/95[th] uncertainty interval (blue shaded area) and the 2009 average Q (dashed grey lines).



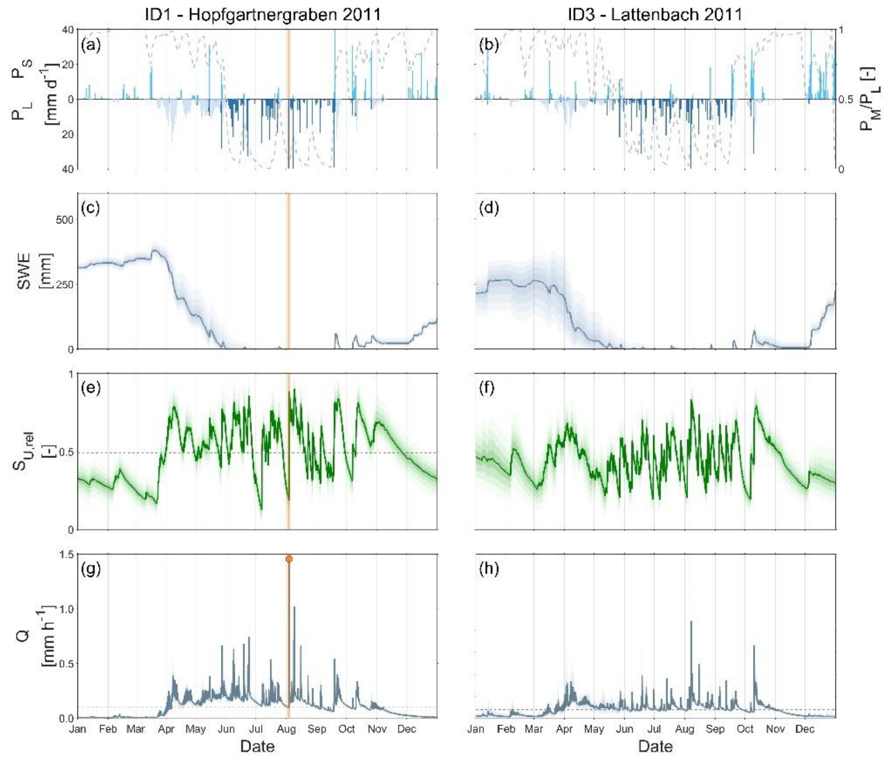
All catchments 2010

Figure S8. Hydrological variables of study catchments ID1 and ID3 for the year 2010. (a), (b) median modelled snowfall P_S (light blue) and liquid precipitation P_L, distinguishing snow melt (light grey-blue) and rainfall (dark blue), the dashed line indicates the fraction of snowmelt to the total liquid water input, i.e. P_M/P_L; (c), (d) median modelled snow water equivalent SWE (solid blue line) and the 5/95th uncertainty interval (blue shaded area); (e), (f) median modelled relative soil moisture S_U (solid green line), the 5/95th uncertainty interval (green shaded area) and the 2010 average S_U (dashed grey line); (g), (h) median modelled stream flow Q (solid blue line), the 5/95th uncertainty interval (blue shaded area) and the 2010 average Q (dashed grey lines). The dark red bar (ID3) indicates the date of observed debris flows and the circle symbol indicates the median modelled channel stream flow Q associated with each debris flow.



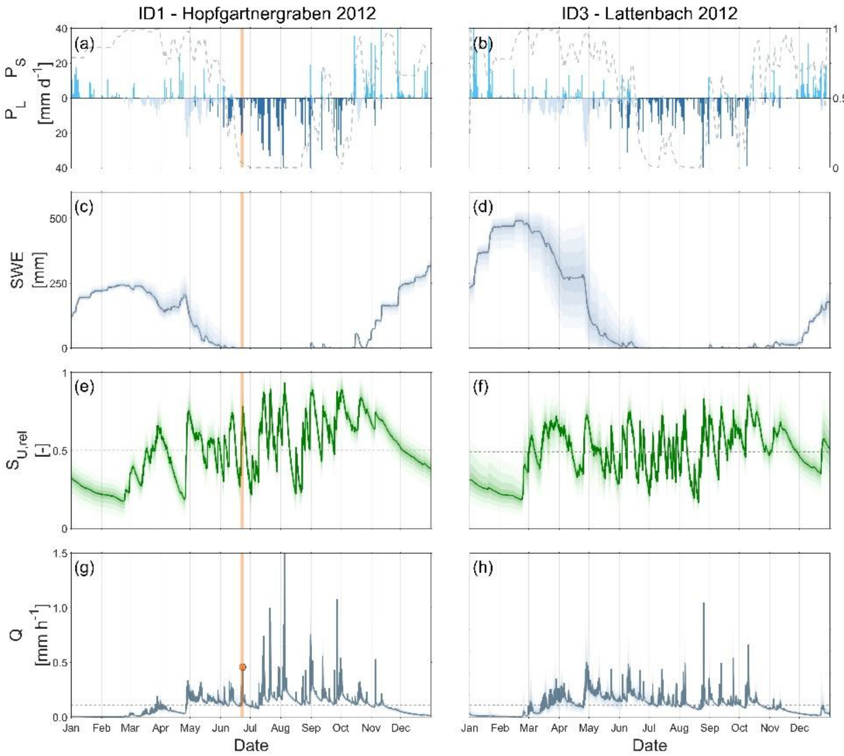
All catchments 2011

Figure S9. Hydrological variables of study catchments ID1 and ID3 for the year 2011. (a), (b) median modelled snowfall P_S (light blue) and liquid precipitation P_L, distinguishing snow melt (light grey-blue) and rainfall (dark blue), the dashed line indicates the fraction of snowmelt to the total liquid water input, i.e. P_M/P_L; (c), (d) median modelled snow water equivalent SWE (solid blue line) and the 5/95th uncertainty interval (blue shaded area); (e), (f) median modelled relative soil moisture S_U (solid green line), the 5/95th uncertainty interval (green shaded area) and the 2011 average S_U (dashed grey line); (g), (h) median modelled stream flow Q (solid blue line), the 5/95th uncertainty interval (blue shaded area) and the 2011 average Q (dashed grey lines). The orange bar (ID1) indicates the date of observed debris flows and the circle symbol indicates the median modelled channel stream flow Q associated with each debris flow.



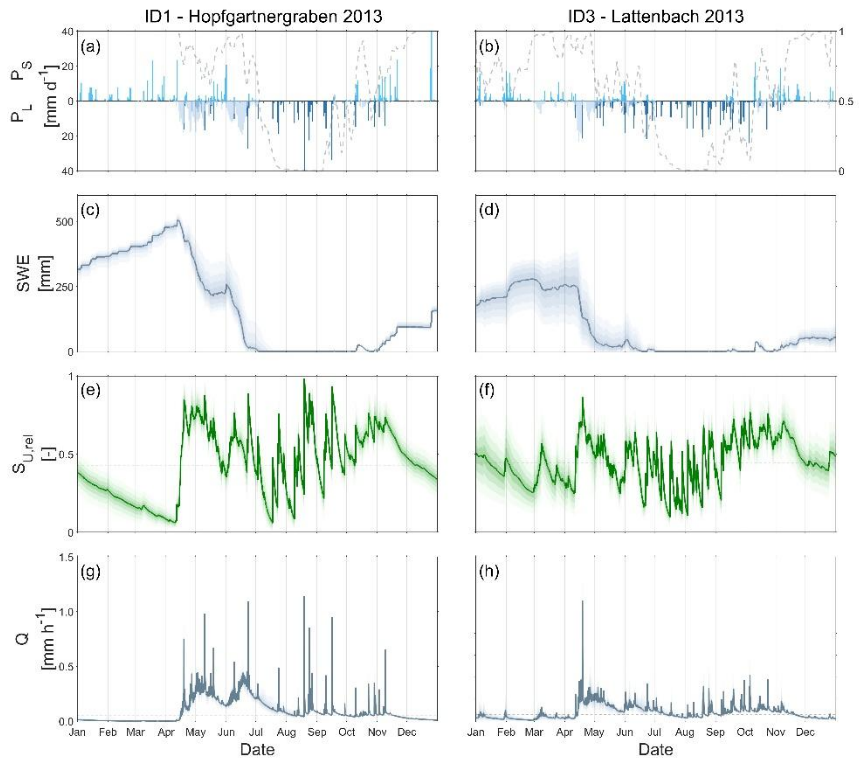
All catchments 2012

Figure S10. Hydrological variables of study catchments ID1 and ID3 for the year 2012. (a), (b) median modelled snowfall P_S (light blue) and liquid precipitation P_L, distinguishing snow melt (light grey-blue) and rainfall (dark blue), the dashed line indicates the fraction of snowmelt to the total liquid water input, i.e. P_M/P_L; (c), (d) median modelled snow water equivalent SWE (solid blue line) and the 5/95th uncertainty interval (blue shaded area); (e), (f) median modelled relative soil moisture S_U (solid green line), the 5/95th uncertainty interval (green shaded area) and the 2012 average S_U (dashed grey line); (g), (h) median modelled stream flow Q (solid blue line), the 5/95th uncertainty interval (blue shaded area) and the 2012 average Q (dashed grey lines). The orange bar (ID1) indicates the date of observed debris flows and the circle symbol indicates the median modelled channel stream flow Q associated with each debris flow.



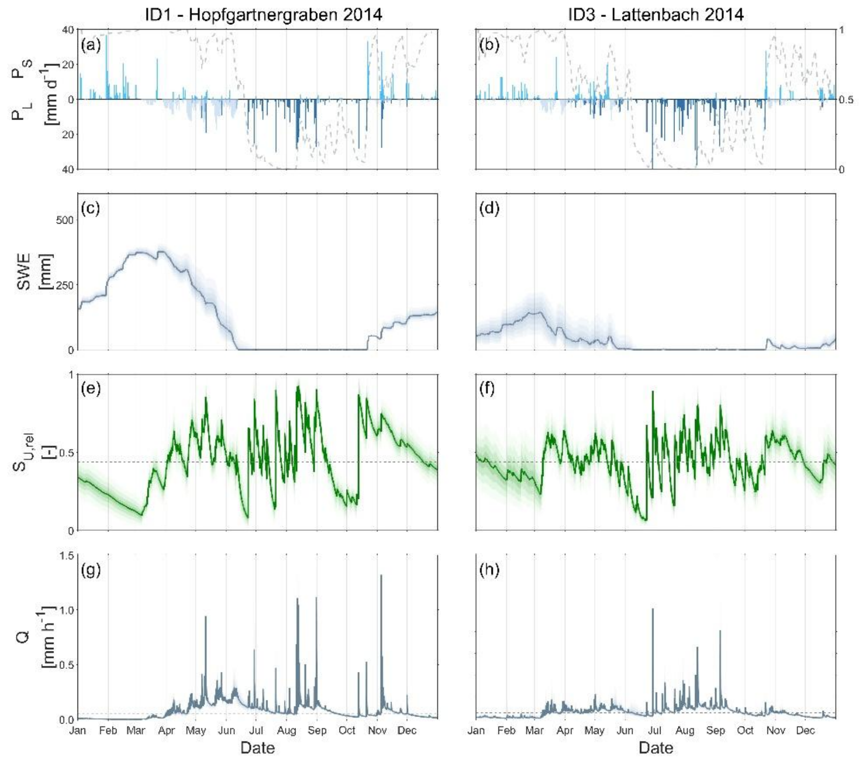
All catchments 2013

Figure S11. Hydrological variables of study catchments ID1 and ID3 for the year 2013. (a), (b) median modelled snowfall P_S (light blue) and liquid precipitation P_L, distinguishing snow melt (light grey-blue) and rainfall (dark blue), the dashed line indicates the fraction of snowmelt to the total liquid water input, i.e. P_M/P_L; (c), (d) median modelled snow water equivalent SWE (solid blue line) and the 5/95[th] uncertainty interval (blue shaded area); (e), (f) median modelled relative soil moisture S_U (solid green line), the 5/95[th] uncertainty interval (green shaded area) and the 2013 average S_U (dashed grey line); (g), (h) median modelled stream flow Q (solid blue line), the 5/95[th] uncertainty interval (blue shaded area) and the 2013 average Q (dashed grey lines).



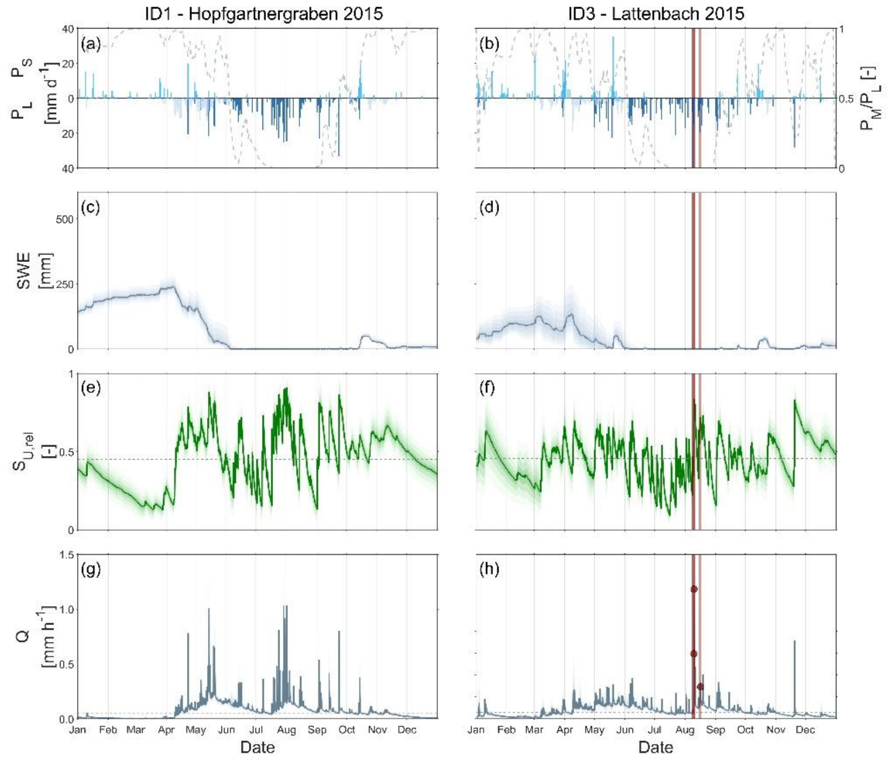
All catchments 2014

Figure S12. Hydrological variables of study catchments ID1 and ID3 for the year 2014. (a), (b) median modelled snowfall P_S (light blue) and liquid precipitation P_L, distinguishing snow melt (light grey-blue) and rainfall (dark blue), the dashed line indicates the fraction of snowmelt to the total liquid water input, i.e. P_M/P_L; (c), (d) median modelled snow water equivalent SWE (solid blue line) and the 5/95th uncertainty interval (blue shaded area); (e), (f) median modelled relative soil moisture S_U (solid green line), the 5/95th uncertainty interval (green shaded area) and the 2014 average S_U (dashed grey line); (g), (h) median modelled stream flow Q (solid blue line), the 5/95th uncertainty interval (blue shaded area) and the 2014 average Q (dashed grey lines).



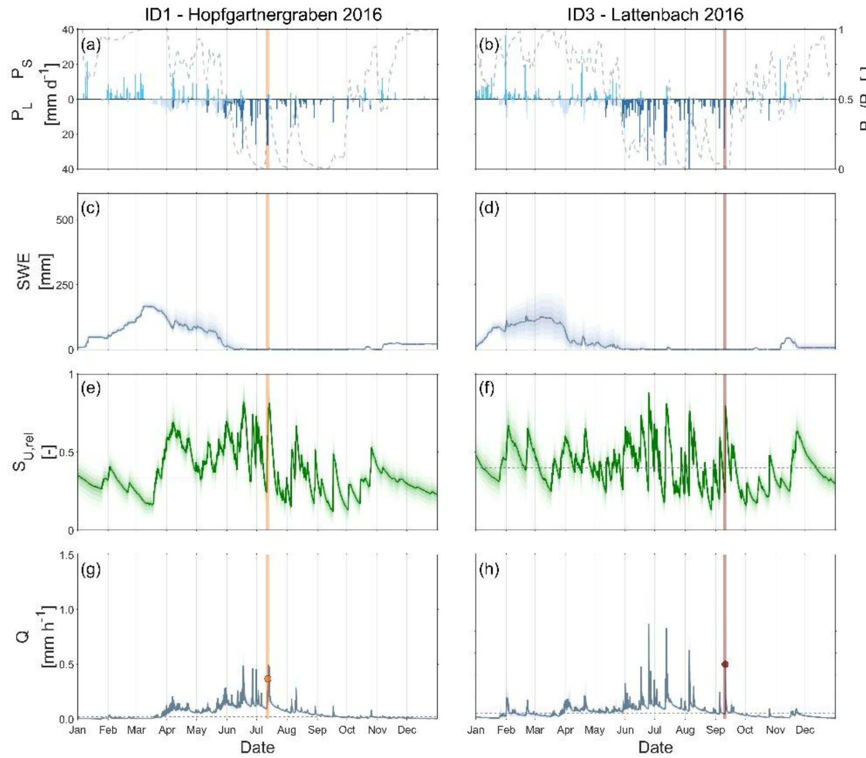
All catchments 2015

Figure S13. Hydrological variables of study catchments ID1 and ID3 for the year 2015. (a), (b) median modelled snowfall P_S (light blue) and liquid precipitation P_L, distinguishing snow melt (light grey-blue) and rainfall (dark blue), the dashed line indicates the fraction of snowmelt to the total liquid water input, i.e. P_M/P_L; (c), (d) median modelled snow water equivalent SWE (solid blue line) and the 5/95th uncertainty interval (blue shaded area); (e), (f) median modelled relative soil moisture S_U (solid green line), the 5/95th uncertainty interval (green shaded area) and the 2015 average S_U (dashed grey line); (g), (h) median modelled stream flow Q (solid blue line), the 5/95th uncertainty interval (blue shaded area) and the 2015 average Q (dashed grey lines). The dark red bars (ID3) indicate the dates of observed debris flows and the circle symbols indicate the median modelled channel stream flow Q associated with each debris flow.



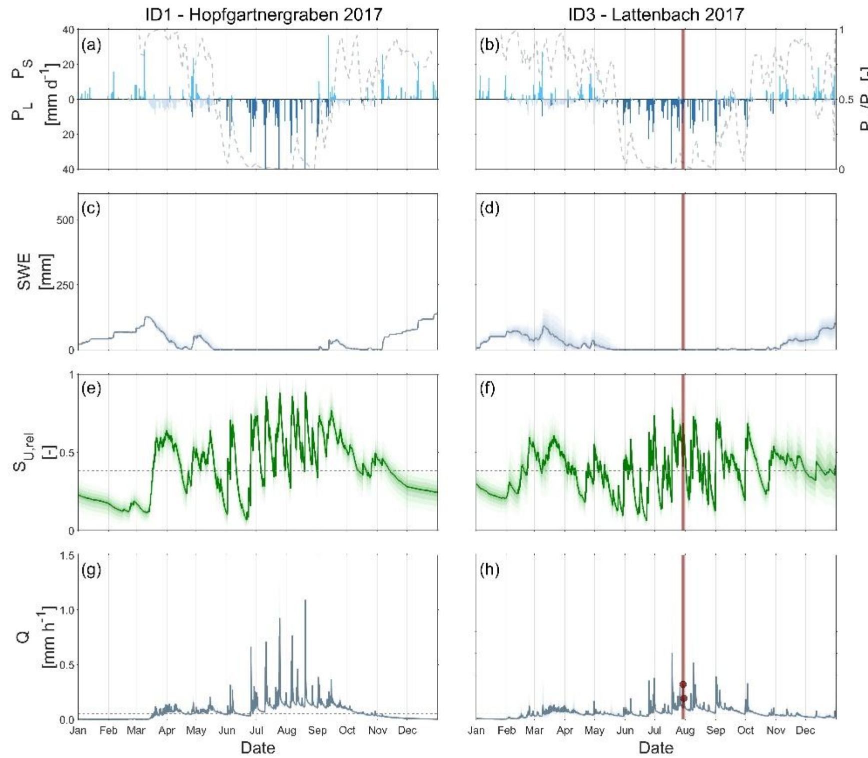
All catchments 2016

Figure S14. Hydrological variables of study catchments ID1 and ID3 for the year 2016. (a), (b) median modelled snowfall P_S (light blue) and liquid precipitation P_L, distinguishing snow melt (light grey-blue) and rainfall (dark blue), the dashed line indicates the fraction of snowmelt to the total liquid water input, i.e. P_M/P_L; (c), (d) median modelled snow water equivalent SWE (solid blue line) and the 5/95th uncertainty interval (blue shaded area); (e), (f) median modelled relative soil moisture S_U (solid green line), the 5/95th uncertainty interval (green shaded area) and the 2016 average S_U (dashed grey line); (g), (h) median modelled stream flow Q (solid blue line), the 5/95th uncertainty interval (blue shaded area) and the 2016 average Q (dashed grey lines). The orange (ID1) and dark red bars (ID3) indicate the dates of observed debris flows and the circle symbols indicate the median modelled channel stream flow Q associated with each debris flow.



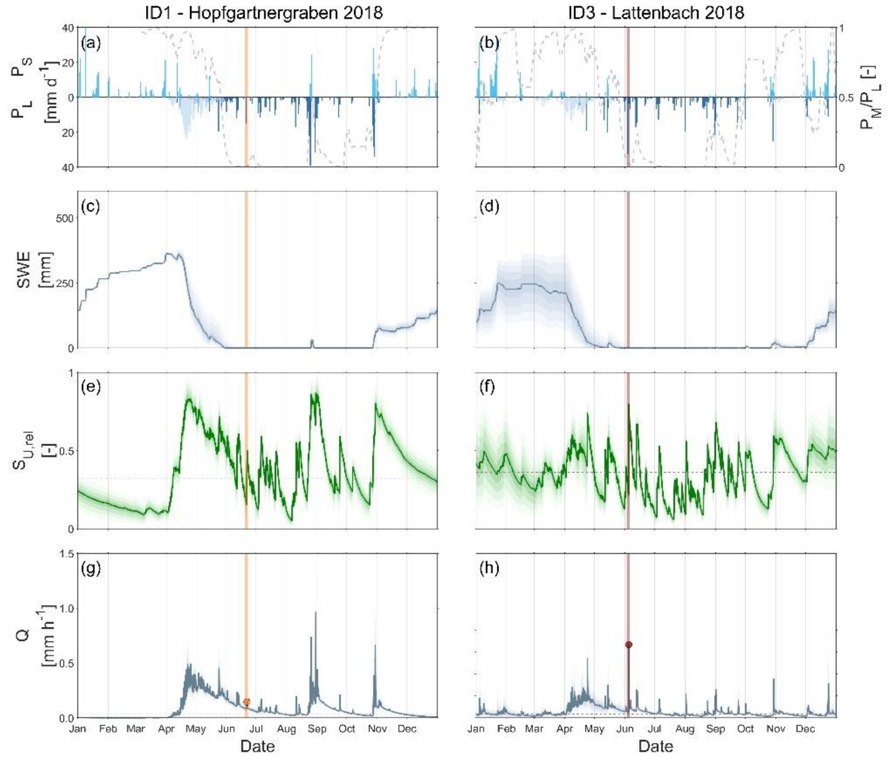
All catchments 2017

Figure S15. Hydrological variables of study catchments ID1 and ID3 for the year 2017. (a), (b) median modelled snowfall P_S (light blue) and liquid precipitation P_L, distinguishing snow melt (light grey-blue) and rainfall (dark blue), the dashed line indicates the fraction of snowmelt to the total liquid water input, i.e. P_M/P_L; (c), (d) median modelled snow water equivalent SWE (solid blue line) and the 5/95th uncertainty interval (blue shaded area); (e), (f) median modelled relative soil moisture S_U (solid green line), the 5/95th uncertainty interval (green shaded area) and the 2017 average S_U (dashed grey line); (g), (h) median modelled stream flow Q (solid blue line), the 5/95th uncertainty interval (blue shaded area) and the 2017 average Q (dashed grey lines). The dark red bars (ID3) indicate the dates of observed debris flows and the circle symbols indicate the median modelled channel stream flow Q associated with each debris flow.



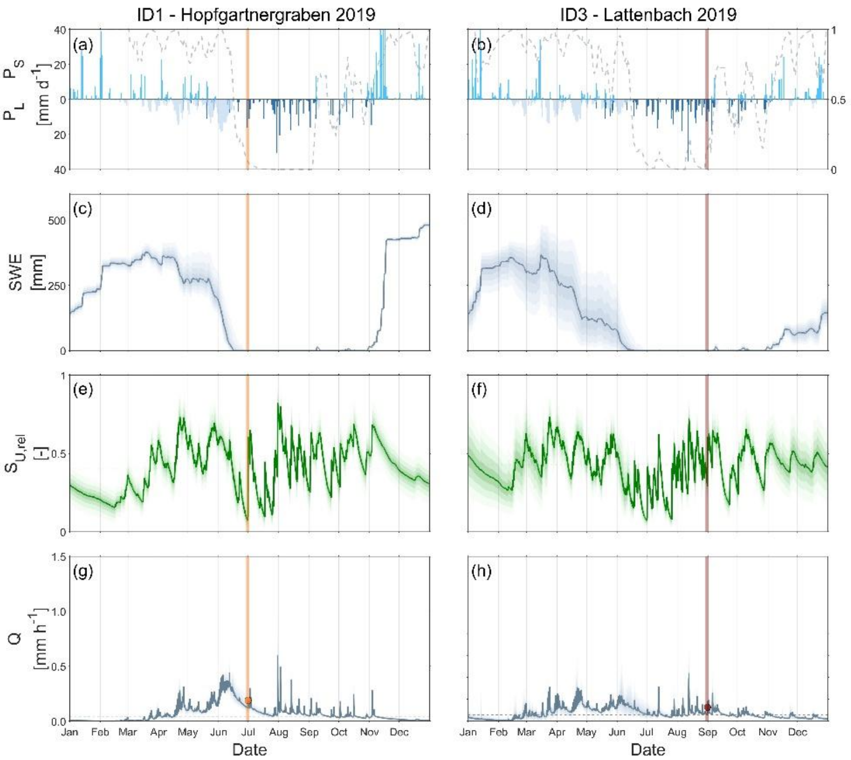
All catchments 2018

Figure S16. Hydrological variables of study catchments ID1 and ID3 for the year 2018. (a), (b) median modelled snowfall P_S (light blue) and liquid precipitation P_L, distinguishing snow melt (light grey-blue) and rainfall (dark blue), the dashed line indicates the fraction of snowmelt to the total liquid water input, i.e. P_M/P_L; (c), (d) median modelled snow water equivalent SWE (solid blue line) and the 5/95th uncertainty interval (blue shaded area); (e), (f) median modelled relative soil moisture S_U (solid green line), the 5/95th uncertainty interval (green shaded area) and the 2018 average S_U (dashed grey line); (g), (h) median modelled stream flow Q (solid blue line), the 5/95th uncertainty interval (blue shaded area) and the 2018 average Q (dashed grey lines). The orange (ID1) and dark red bars (ID3) indicate the dates of observed debris flows and the circle symbols indicate the median modelled channel stream flow Q associated with each debris flow.



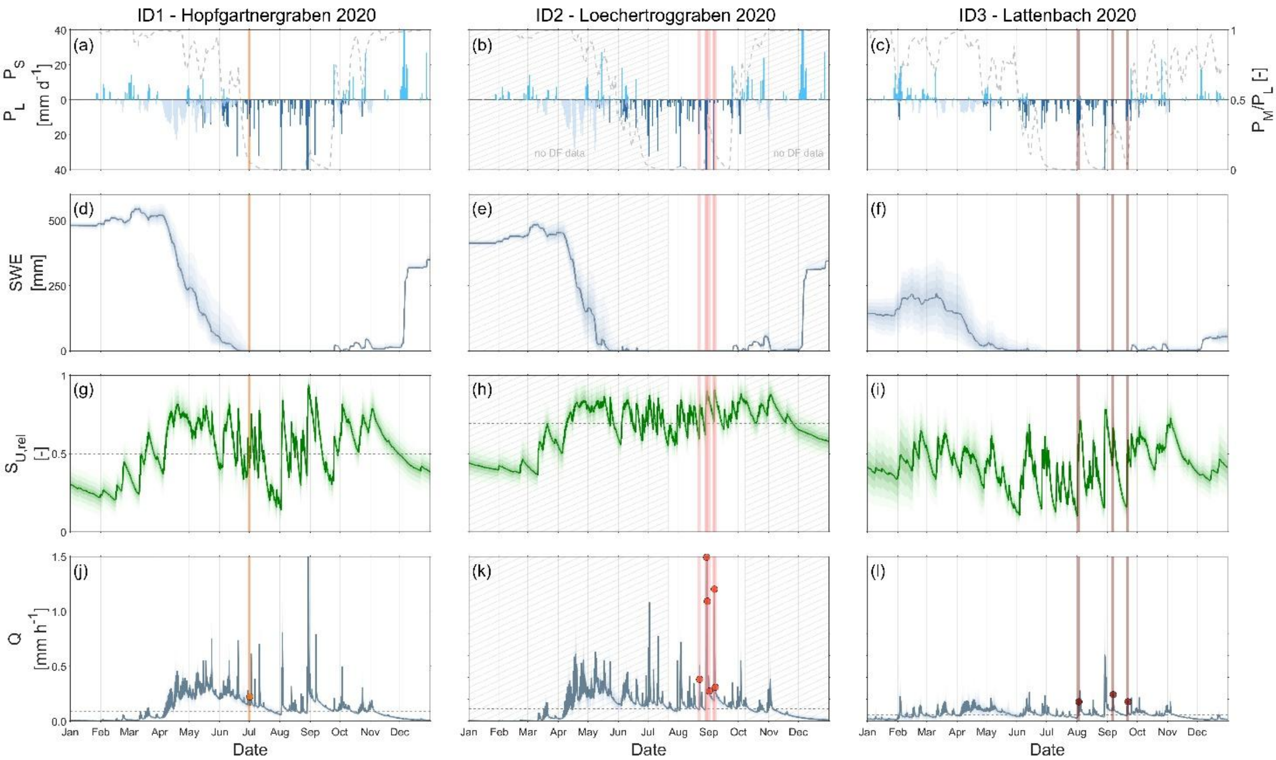
All catchments 2019

Figure S17. Hydrological variables of study catchments ID1 and ID3 for the year 2019. (a), (b) median modelled snowfall P_S (light blue) and liquid precipitation P_L, distinguishing snow melt (light grey-blue) and rainfall (dark blue), the dashed line indicates the fraction of snowmelt to the total liquid water input, i.e. P_M/P_L; (c), (d) median modelled snow water equivalent SWE (solid blue line) and the 5/95[th] uncertainty interval (blue shaded area); (e), (f) median modelled relative soil moisture S_U (solid green line), the 5/95[th] uncertainty interval (green shaded area) and the 2019 average S_U (dashed grey line); (g), (h) median modelled stream flow Q (solid blue line), the 5/95[th] uncertainty interval (blue shaded area) and the 2019 average Q (dashed grey lines). The orange (ID1) and dark red bars (ID3) indicate the dates of observed debris flows and the circle symbols indicate the median modelled channel stream flow Q associated with each debris flow.



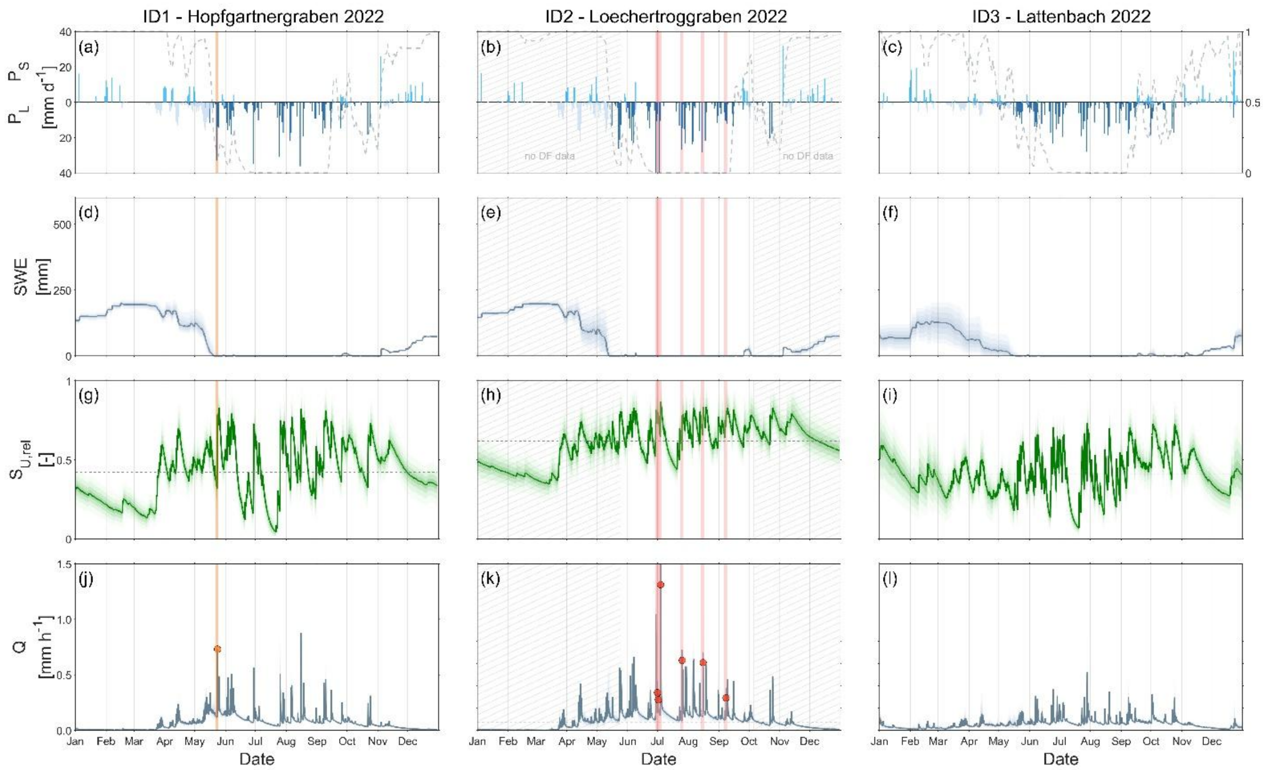
All catchments 2020

Figure S18. Hydrological variables of the three study catchments ID1 – ID3 for the year 2020. (a) – (c) median modelled snowfall P_S (light blue) and liquid precipitation P_L, distinguishing snow melt (light grey-blue) and rainfall (dark blue), the dashed line indicates the fraction of snowmelt to the total liquid water input, i.e. P_M/P_L; (d) – (f) median modelled snow water equivalent SWE (solid blue line) and the 5/95th uncertainty interval (blue shaded area); (g) – (h) median modelled relative soil moisture S_U (solid green line), the 5/95th uncertainty interval (green shaded area) and the 2020 average S_U (dashed grey line); (j) – (l) median modelled stream flow Q (solid blue line), the 5/95th uncertainty interval (blue shaded area) and the 2020 average Q (dashed grey lines). The orange (ID1), red (ID2) and dark red bars (ID3) indicate the date of observed debris flows and the circle symbols indicate the median modelled channel stream flow Q associated with each debris flow. The grey hatched area for ID2 indicates periods with no debris flow data.



All catchments 2022

Figure S19. Hydrological variables of the three study catchments ID1 – ID3 for the year 2022. (a) – (c) median modelled snowfall P_S (light blue) and liquid precipitation P_L, distinguishing snow melt (light grey-blue) and rainfall (dark blue), the dashed line indicates the fraction of snowmelt to the total liquid water input, i.e. P_M/P_L; (d) – (f) median modelled snow water equivalent SWE (solid blue line) and the 5/95th uncertainty interval (blue shaded area); (g) – (h) median modelled relative soil moisture S_U (solid green line), the 5/95th uncertainty interval (green shaded area) and the 2022 average S_U (dashed grey line); (j) – (l) median modelled stream flow Q (solid blue line), the 5/95th uncertainty interval (blue shaded area) and the 2022 average Q (dashed grey lines). The orange (ID1) and red bars (ID2) indicate the date of observed debris flows and the circle symbols indicate the median modelled channel stream flow Q associated with each debris flow. The grey hatched area for ID2 indicates periods with no debris flow data.



Regional thresholds

Figure S20. The six bivariate regional debris flow thresholds based on the combined debris flows of all three study catchmetns ID1 – ID3. (a) precipitation duration and intensity threshold P_d-P_i, (b) rainfall duration and intensity threshold $P_{R,d}$-$P_{R,i}$, (c) liquid precipitation duration and intensity threshold $P_{L,d}$-$P_{L,i}$, (d) soil moisture and liquid precipitation intensity threshold S_U-$P_{L,i}$, (e) discharge and liquid precipitation threshold Q-$P_{L,i}$ and (f) discharge and soil moisture threshold Q-S_U. The thin dashed lines indicate the regional thresholds and the light shaded areas the associated 5th-95th uncertainty intervals. The bold lines show the local thresholds and the shaded areas the 5th-95th uncertainty intervals. The orange circles indicate observed debris flow event, representing true positives TP when plotting above and false negatives FN when plotting below the thresholds. The light grey dots indicate no-debris flow events, representing false positives FP when plotting above and true negatives TN when plotting below the thresholds. The horizontal and vertical orange error bars indicate the 5-95th uncertainty of the respective modelled variables. Note, error bars of P_R and P_L not shown as the uncertainties were minor. Thresholds with $ß \leq -100$ converge towards vertical thresholds and are thus here for brevity labelled as univariate thresholds in the form of x = const.