Hydro-geomorphological response to changes in the spatial structure of extreme rainfall in a warmer world

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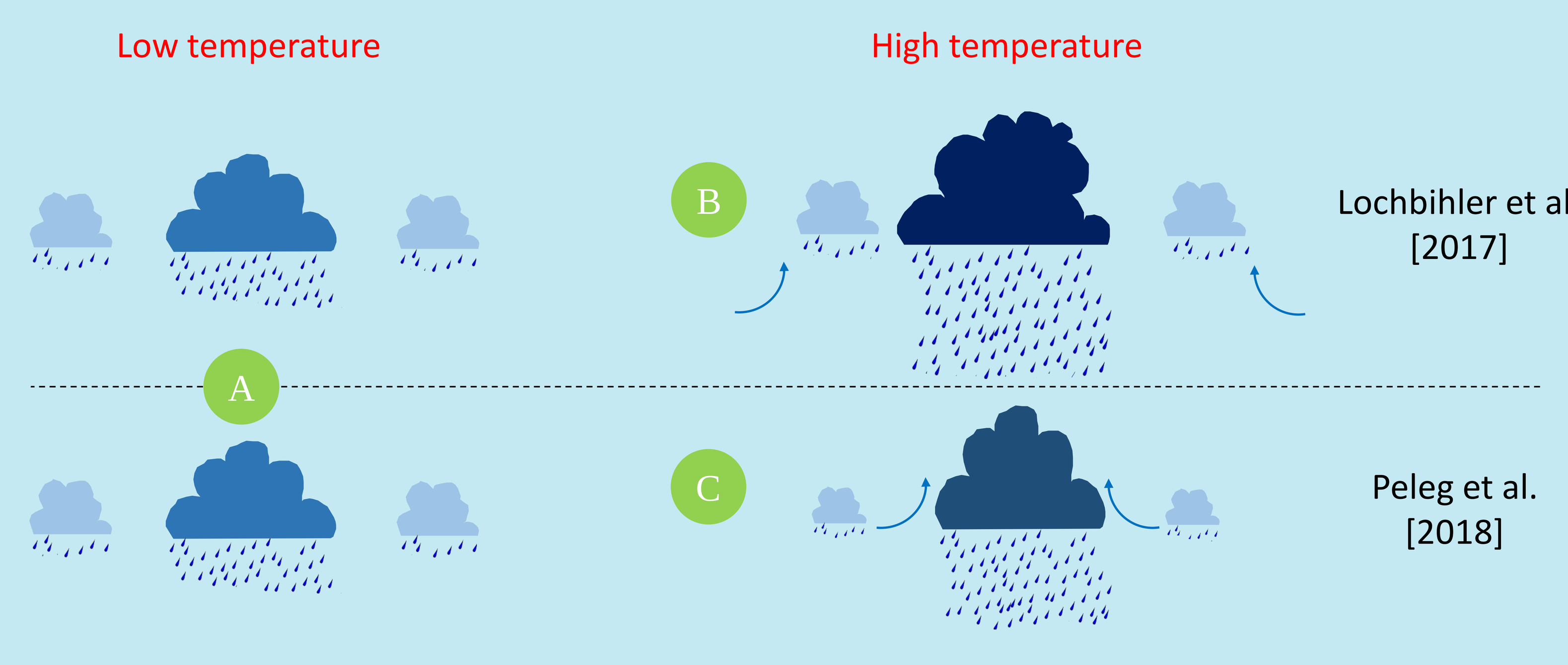
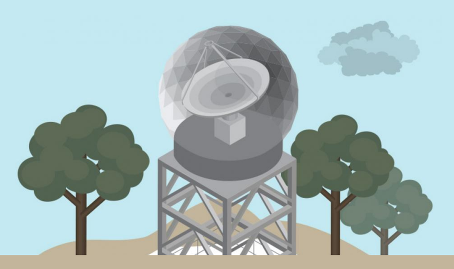


A – a hypothetical storm; B - the storm is intensifying and growing. Humidity source is external to the storm; C – internal re-distribution of the humidity within the storm leads to intensification at the high rainfall zone (but the area remains unchanged) and to weakening at the low rainfall zone (and the area decreases).



Rainfall Spatial Structure

- Spatio-temporal rainfall variability plays an important role in the hydro-morphological response of catchments, affecting streamflow and sediment transport volumes, peaks and time to peaks.
- The intensity of heavy rainstorms is sensitive to warming due to warmer air having an increased water vapor holding capacity, which in saturated conditions follows the Clausius-Clapeyron (CC) relationship.
- So far, only few studies have used remotely sensed data to analyse the impact of increasing temperatures on the spatial characteristics of heavy rainfall. For example, Peleg et al. (2018) reported a re-distribution of available humidity from the low intensity regions of the rain field toward the high-intensity regions, while Lochbihler et al. (2017) observed that the area and the intensity of heavy rainfall increase with rising temperatures.
- The question of the sensitivity of hydro-morphological response to spatial changes in high-resolution rainfall fields has not been extensively explored so far.

1 Experimental Setup

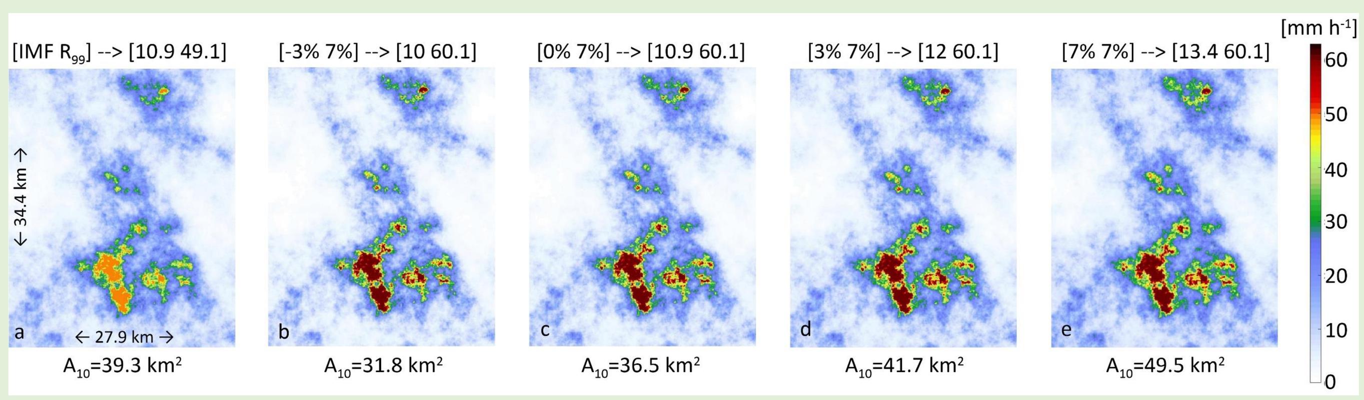
The numerical experiment is composed of two steps:

I. Stochastically simulating convective and stratiform rainfall fields using a numerical rainfall generator (RG) model to follow a design storm characterized by a Gaussian shape that is assumed representative of a heavy rainfall event. The rainfall fields are modified using the RG to follow 4 “temperature increase scenarios” and 4 “areal rainfall scenarios”. In all of the scenarios, the peak rainfall intensity at the grid scale is assumed to intensify at a rate of 7% °C^{-1}, which corresponds with a fully saturated air column.

ΔT=1°C	ΔT=2°C	ΔT=3°C	ΔT=4°C
7% °C^{-1}	7% °C^{-1}	7% °C^{-1}	7% °C^{-1}
3% °C^{-1}	3% °C^{-1}	3% °C^{-1}	3% °C^{-1}
0% °C^{-1}	0% °C^{-1}	0% °C^{-1}	0% °C^{-1}
-3% °C^{-1}	-3% °C^{-1}	-3% °C^{-1}	-3% °C^{-1}

Temperature and rainfall intensity scenarios. Colors represent qualitatively changes in the area of the intense rainfall, from a large increase (dark blue) to a large decrease (dark green).

II. In the second stage, the multiple stochastic realizations of design storms that were simulated for each of the scenarios were fed into a landscape evolution model (CAESAR-Lisflood) to simulate the hydro-morphological response.



(a) An example of a stratiform simulated rainfall field for a given time step. (b-e) plots of the rainfall field with 4 different “areal rainfall scenarios” and for a specific “temperature scenario” of ΔT=3°C. IMF refers to changes in the mean areal rainfall [% °C^{-1}] and R99 refer to changes in the peak rainfall intensity [% °C^{-1}] in comparison to (a); the absolute values of mean areal rainfall and peak rainfall intensity are given in parentheses [mm h^{-1}]. A_{10} refers to the total area [km²] above a rain intensity threshold of 10 mm h^{-1}.

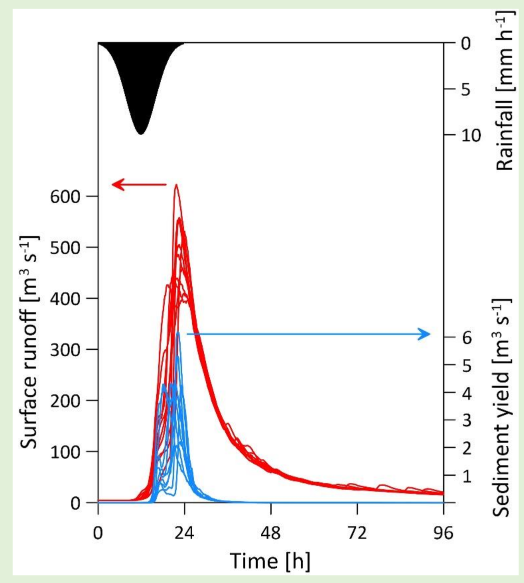
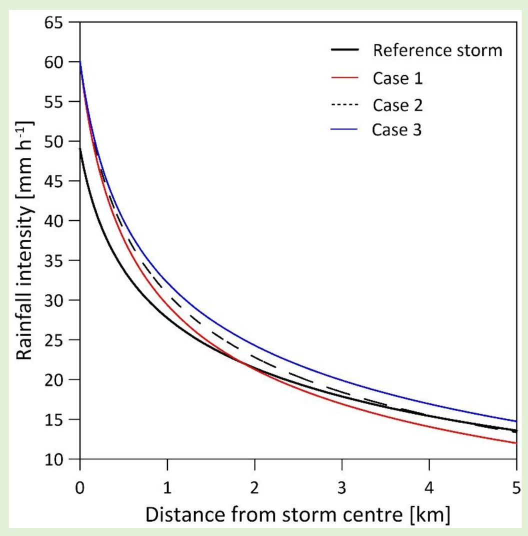


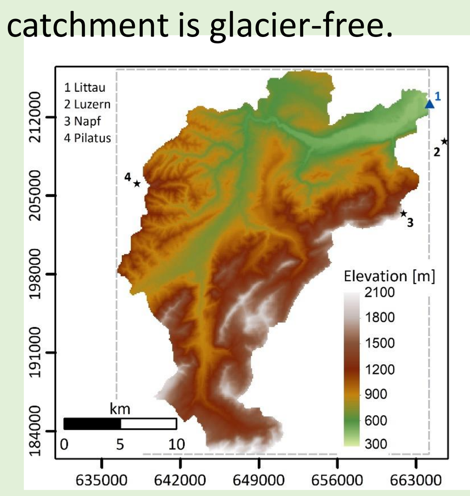
Illustration of the rainfall intensity over the catchment (black area) and the respectively generated stream runoff (red lines) and sediment yields (blue lines) from 10 stochastic rainfall realizations produced with the rainfall generator.



Schematic illustration of the changes to the spatial structure of storms with increasing temperature.

2 Study Site

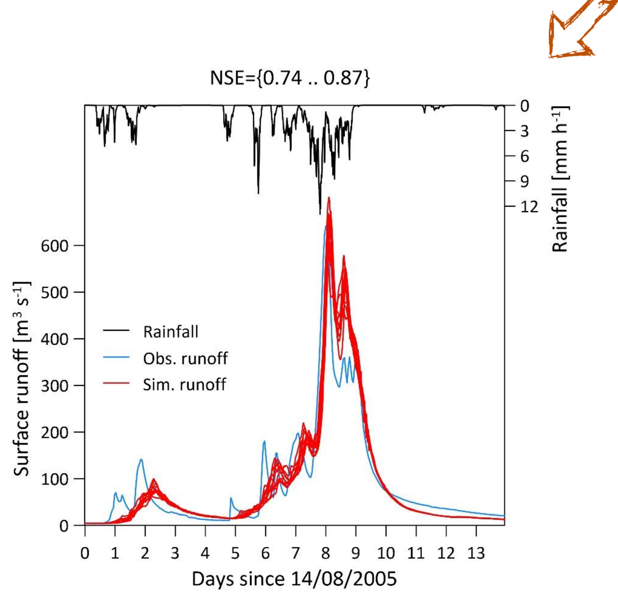
- The study was conducted in the Alpine Kleine Emme catchment, located in central Switzerland (8°E 47°N).
- There are several reasons for the selection of this catchment:
  - I. Intense convective rainfall events are common over the region during summer and rainfall is associated with high space-time variability.
  - II. The catchment is well monitored in terms of rainfall and streamflow.
  - III. The streamflow is close to natural conditions; the catchment is glacier-free.
  - IV. The catchment is representative in terms of topographic, hydrological and geomorphological features of a typical Alpine catchment.



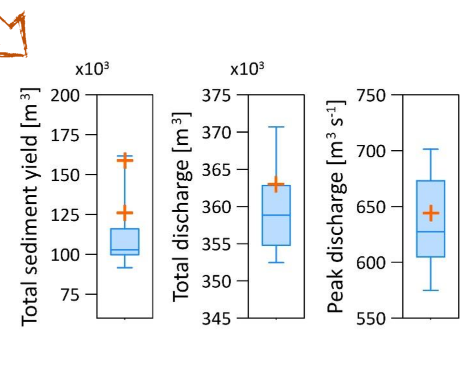
Map of the catchment with the location of the hydrometric station (blue triangle) and the locations of the meteorological stations (black stars). Dashed grey line represents the domain with simulated rainfall.

3 August 2005 Extreme Rainfall and Flow Event

The parameters of the CAESAR-Lisflood model were calibrated based on the August 2005 heavy rainfall and streamflow event.



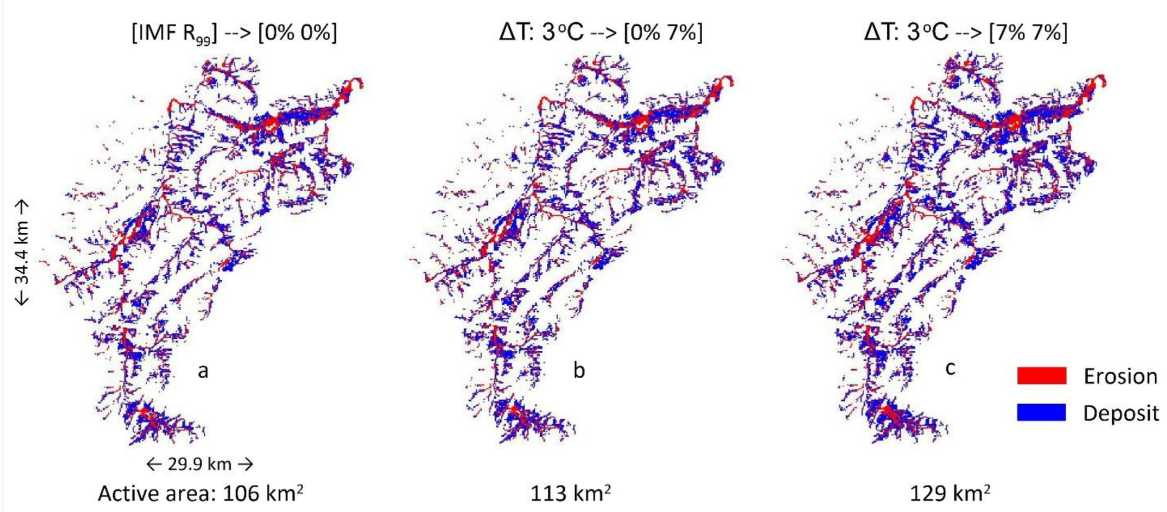
Observed (blue) and simulated (red) streamflow for the August 2005 event. The black line represents the mean areal rainfall over the catchment.



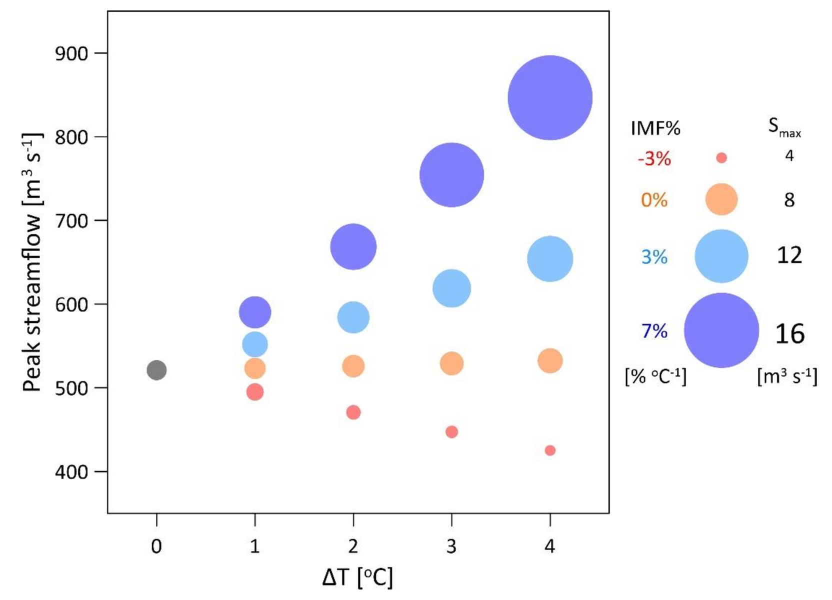
Box-plots showing the median (horizontal line), 25-75th percentile range (shaded area) and maximum and minimum range (bounded with lines) of the total sediment yield, total streamflow volume and peak streamflow from the 10 spatial rainfall realizations. The orange ‘+’ symbols represent the observed data for the total and peak streamflow, and the estimated range of the total sediment yield.

4 Results

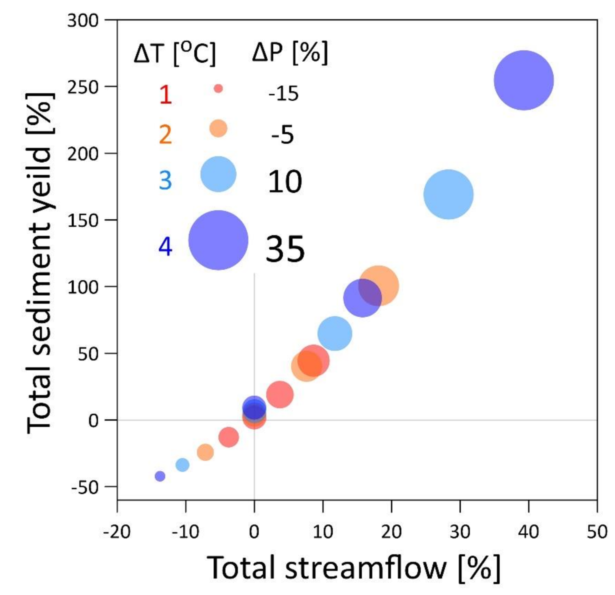
The sensitivity of the hydro-morphological response to the changes in rainfall spatial structure was examined in terms of peak streamflow and sediment yield, for the total volumes of streamflow and sediment yield and for the inundated area and the area subjected to erosion or deposition.



An example to the changes in the area of erosion (red) and deposition (blue) with stratiform storm spatial characteristics. IMF stands for changes in the areal rainfall and R_{99} for changes in the peak rainfall intensity at the grid-scale.



Response of the peak streamflow (y-axis) and peak sediment yield (symbol size, S_{max}) at the outlet of the catchment to changes in the rainfall spatial structure with temperature. Peak rainfall intensity increases by 7% °C^{-1} for all points. Different colors represent a mean areal rainfall intensity decrease of -3% °C^{-1} (red), not changing (orange), and increase of 3% °C^{-1} (blue) and 7% °C^{-1} (purple). Reference (base scenario) for the sensitivity is the single point at ΔT=0 (grey).



Changes in the total sediment yield (y-axis) as a function of the changes in total streamflow (x-axis) in relation to the changes in total rainfall amounts (symbol size, ΔP). The relevant temperature scenario (ΔT) is expressed by the color of the symbols (1°C – red, 2°C – orange, 3°C – blue and 4°C – purple). The reference to compute the changes is the total streamflow and sediment transport of the base scenario (at ΔT=0).

5 Conclusions

- Results demonstrated that hydrological and morphological related variables are sensitive to changes in the rainfall spatial structure, with a much higher sensitivity for the morphological components (e.g. peak sediment yield) in comparison to the hydrological components (e.g. peak streamflow).
- Regardless of uncertainty, predicting changes in hydro-morphological response require plausible scenarios of how both the peak rainfall intensity and the mean areal rainfall are going to change in a different climate, as was done here.
- Neglecting changes in the rainfall spatial structure may be misleading and lead to over-prediction of the hydro-morphological response.

	Stratiform rainfall			Convective rainfall		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
Peak streamflow	- -	o	+ +	-	+	+ +
Peak sediment yield	- -	+	+ + +	o	+ +	+ + +
Total streamflow	- -	o	+ +	- -	o	+ +
Total sediment yield	- -	+	+ + +	-	+ +	+ + +
Inundated area	-	o	+	- -	o	+
Area of erosion and deposition	- -	+	+ + +	-	+	+ + +

A qualitative summary of the hydro-morphological response to the three main studied cases for the rainfall spatial structure corresponding to stratiform and convective types. For all three cases, the peak rainfall intensity at the grid scale intensifies. Case (1) total rainfall amount decreases, area of heavy rainfall decreases; (2) total rainfall amount remains unchanged and area of heavy rainfall slightly decreases; and (3) total rainfall amount increases, area of heavy rainfall increases. The response varies between a strong negative response (- - -), no change (o) and a strong positive response (+ + +).

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References

- Peleg, N., Marra, F., Fatichi, S., Molnar, P., Morin, E., Sharma, A., and Burlando, P. (2018). Intensification of convective rain cells at warmer temperatures observed from high-resolution weather radar data. *Journal of Hydrometeorology*, 19(4), 715-726.
- Peleg, N., Skinner, C., Fatichi, S., and Molnar, P. (2020). Temperature effects on spatial structure of heavy rainfall modify catchment hydro-morphological response, *Earth Surface Dynamics*, 8, 17-36.