Linking frequency of rainstorms, runoff generation and sediment transport across hyperarid talus-pediment slopes

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Summary

In short: we provide quantitative analyses of runoff-generating rain cells and their geomorphic impact on hyperarid talus-pediment slopes. Full extent of hillslope runoff occurs only under rainstorms with $\geq 100$-years return interval. Sheetwash efficiency rises with downslope distance; $\geq 100$-years return interval storms are capable of transporting surface clasts. The erosion efficiency of these discrete rare events highlights their potential importance in shaping the landscape of arid regions.
Talus slopes
dominant geomorphic elements and primary runoff and sediment contributors
(e.g., Pinheiro et al., 2017, Duszyński et al., 2019)

Modified from Gutiérrez et al., (1998)

Talus flatirons
considered as geomorphic evidence of climate oscillations (e.g., Schmidt 2009, Gutiérrez et al., 1998)
Two-phase conceptual model

(e.g., Schumm and Chorley 1966, Gerson, 1982, Schmidt 1989b, 2009)

In wet conditions: caprock-derived material accumulates within the lower scarp slope. The slope is considered as stable.

In arid conditions: dissection and gullying lead to the separation of the slope from the cliff.

Flatiron evolution was hypothesized to be associated with glacial-interglacial climatic cycles.

Modified from Schmidt (1989b)
However, in arid areas, many previous arguments linking the evolution of such landforms with climate were actually based on inferences; relevant landforms were never dated to support this notion.

In dry regions, a shift toward a climate characterized by more frequent extreme storms can significantly increase erosion, even when the mean climatic conditions do not become wetter.

Only a few previous studies focused on evaluating and quantifying the link between extreme rainstorms, runoff, and erosion on arid hillslopes.

We ask:

- How often runoff is generated over the slopes?
- Which extreme rainfall events, if at all, drive the evolution of talus-pediment sequences?
How can we get long-term implications about short-term processes?

1. Collecting rainfall\topographic data
2. Construct field rainfall simulator experiments of IDF-based \textit{designed storms} on a plot scale ($2 \, m^2$)
3. Simulate the \textit{designed storms} with grid-based numerical modeling on slope scale
Three generation of talus flatirons, separated by rills and gullies.

Complex hydrological response in a convective rain environment.

Mean annual precipitation < 80 mm.

The study site:

Tzuk Tamrur

Courtesy of Ronen Boroda
A design storm is a theoretical storm event based on rainfall intensities associated with frequency of occurrence (B)

Three synthetic storms (30-min) were designed, representing 5- (20%), 50- (2%) and 100-years (1%) return periods (C)

What is IDF-based designed storms?
Field rainfall simulator experiments

- We used a portable rainfall simulator designed and constructed by Abudi, Carmi, and Berliner (2012)
- Rainfall simulation experiments were conducted over three separate 1x2 m² plots, on two talus slopes of the Tzuk Tamur mesa
- The three **designed storms** were applied on the slopes. Runoff and suspended sediment load has been measured
Monitoring the 2017\18 hydrological season

Field installed time lapse cameras (TLC) used to monitor selected slopes during rainstorms (click here for camera view). In each video, we searched for runoff generation and feedbacks concerning sediment transport.

1-min resolution rain gauge network

X-band mini weather radar (60 x 60 m², 1 min) Allegretti et al., (2012)
GB-HYDRA (Rinat et al., 2018)

GB-HYDRA model which is an event-scale, physically-based, fully distributed hydrological model

Here we used the GB-HYDRA to **simulate the designed storm in slope-scale**

We used the hillslope-runoff module that was specifically designed to calculate at a high-resolution the water budget, infiltration, runoff generation and its routing down the slope and, maximum shear stress on a **pixel-by-pixel basis**

Infiltration and local runoff generation is computed by a **specifically modified version** of the Soil Conservation Service (SCS) conceptual method (Chow, Maidment, & Mays, 1988)
Morphometric analysis and grain size measurements

A mesa capped by resistant Campanian cherts that overlie a much softer Santonian chalk, on which the sequence of talus flatirons occurs.

Talus-flatiron ages systematically increase with distance from the cliff (Boroda 2011, 2013)

Gradients decrease with the distance from the cliff.
Concave upward slopes

Grainsize trend with talus gradient and age

(b) d50

Grain size [mm]

Slope [deg]

(a) A-A'

Elevation [m]

Distance [m]

Slope [m/m] x 10^0

Distance [m]
From the Rainfall simulator result:
No runoff is observed for rain intensify <12 mm h\(^{-1}\) for a duration of 5 min

Radar analysis and filming:
No runoff is observed for storms with rain intensity <22 mm h\(^{-1}\) for a duration of 5 min

Suggested rainfall threshold: 5-min rain with intensity exceeding 14-22 mm h\(^{-1}\)

Considering the above threshold, it is possible to examine the runoff contribution area within a watershed during a storm (next slide)
For the most intense storms in our database, covering only a portion of the watershed, local runoff is generated (3%-0%, 41%-30%, 39%-20%, from left to right respectively)
Maximal rain intensity gradient of 11% over a distance of 100 m

Low rain cell velocity (8-10 m/s)

Relatively small cell area (20-35 km²)

Based on 52 years gauges record:
1-3 events per year generate local runoff at the study site
The frequency of full extent hillslope overland flow

Hydrological simulations were performed for 5, 50 and 100 years return period synthetic storms.

Runoff contributing area of the 100-year (1%) rainstorm is the entire slope area (100% contributing area). Under the 5- and 50-years storms, runoff generated in the uppermost part of the slope does not reach the base of the slope due to infiltration (83% and 43% contributing area, respectively)
Which storm could mobilize clasts on the slope surface?

A set of shear-stress simulations was applied to different combinations of gradients and slope lengths.

For each simulation, we calculated the transportable grain size using the maximal shear stress generated in each slope-length combination.

The results of 100-years storms are summarized in the contour figure.

For example, for 30° and 50 m slope, the maximal shear stress exert by the 100-years sheetwash is capable of transporting clasts of 19 mm (D50) or smaller.
Which storm could mobilize clasts on the slope surface?

We compare the model simulations results (gray contours) with field grainsize measurements (filled colored circles).

Blue and red circles denote transport and no-transport, respectively (we consider sheet flow is able to transport sediment where the calculated (gray contour) value is greater than the measured clasts size (filled colored circles)).

The sheetwash generated by the 100-year storm can transport the observed clasts on all the slopes with low gradients. *No transportable grainsize for 5- and 50-years return periods storms.
Which storm could erode the slope surface?

We also calculated the potential transported grain size for the 5, 50 and 100-years storm along a characteristics concave up slope:

The return period for runoff generation over the entire length of talus-pediment slopes is at least 100 years (hillslope runoff from more frequent storms includes only part of the slope).

100-years storm (black curve) can produce runoff and sheetwash with shear stress that is high enough to trigger clast mobilization at a distance of ~80 m from the cliff.
Summary and conclusions

- Frequency of local runoff generation over the study site (1-3 times per year)
- The frequency of full extent hillslope runoff is 1 in 100-years. The contributing area for hillslope runoff from more frequent storms declines dramatically and includes only part of the slope.
- 100-years storm (and rarer) can potentially trigger clast mobilization over the lower part of the slope.
- 100-years storms and rarer are most probably responsible also for forming the observed rills, which eventually disconnect the slopes from the cliff.
- The erosion efficiency of these discrete rare events highlights their potential importance in shaping the landscape of arid regions.
Questions?

Check out our paper in ESPL or contact directly by email: yuval.shmilovich@mail.huji.ac.il
Appendix 1. Runoff generation over Tzuk Tamrur slopes during the 25 Apr 2018 rainstorm. (a) TLC image captured 4-min after the beginning of the rainstorm and (b) image captured 6-min later.
References


