Extreme Floods as Agents of Landscape Evolution: Modeling the 2013 Front Range Flood, Colorado, USA

Mariela Perignon and Greg Tucker
CIRES and Department of Geological Sciences, University of Colorado, Boulder, CO

Motivation

During the 2013 Front Range flood, patterns of geomorphic activity varied dramatically between closely spaced basins. Many small basins mobilized very high volumes of sediment for large distances.

- What are the differences in streamflow and sediment transport between small and large watersheds during an extreme precipitation event?
- What processes or characteristics could cause this variability in response to any individual event?

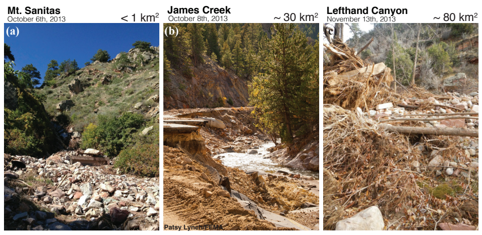
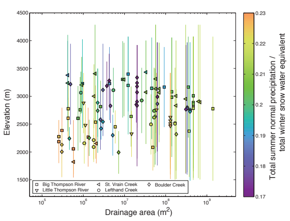


Figure 1: Photographs of **three small watersheds** near Boulder following the 2013 Front Range flood. (a) Drainage on the eastern slope of Mt. Sanitas with >1 m of newly deposited debris. Boulder on top of pump building is 70 cm across. (b) James Creek and undercut road near Jamestown, CO showing several meters of vertical and lateral incision. (c) Debris on the floodplain of Lefthand Creek, downstream of the confluence with James Creek. Top of debris pile is >2 m above the bed of the channel. Large rock slab at the top of the pile is 30 cm thick.

Differences in long-term average runoff between basins



At high elevations, uniform peak discharges from snowmelt floods and a low likelihood of storm runoff result in channels with limited flow conveyance.

Below 2300 m, summer precipitation is dominated by convective thunderstorms with small footprints and short durations, so the relative size of basins compared to the storms controls the spatial distribution of change. Any one small basin is unlikely to be the target of a given storm, and large basins don't "feel" individual thunderstorms.

Figure 2: Relative contribution of summer rainfall and winter snowfall to the annual precipitation budget (as the ratio of the total summer normal precipitation and total winter snow water equivalent - symbol color) for 140 nested subcatchments in the study area, grouped by basin (symbol shape), plotted at the maximum drainage area and mean elevation in each subcatchment. Vertical lines span the range of elevations with the symbol placed at the mean. Low ratios correspond to watersheds that receive higher proportions of snow to rain compared to watersheds with high ratios.

Rainfall during the 2013 Front Range flood

Records of hourly rainfall accumulation were collected from 2135 gaging stations across Colorado for the week of the 2013 Front Range flood. These point data were interpolated across the study basins to create maps of 1-hour precipitation totals for every hour between 6:00 AM MDT on Monday, September 9, 2013 and 11:00 PM MDT on Friday, September 13, 2013.

Calibration of runoff production

There are no high-quality distributed datasets to estimate the loss of runoff across the Front Range. Following *Sten* (1991), we manually calibrated the total output of streamflow at the site of the Boulder Creek USGS streamgage (at 75th St.) against the observed discharge at that station.

An accurate prediction of runoff generation within the study area requires **95% loss** of the total volume of precipitation.

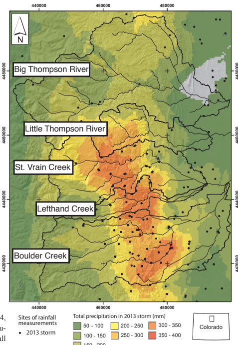


Figure 3: Map of **total rainfall accumulation** (in mm) over 114 hours during the 2013 Front Range flood (September 9-14, 2013), overlain on a 1/3 arcsecond shaded relief map. Hot colors represent higher rainfall totals, and no color indicates total accumulations of less than 50 mm. Study basins are delineated by thick black lines and streams are shows as thin black lines. Small black circles indicate the location of rainfall gages from which data was collected to construct the 2013 storm precipitation maps.

Hydrodynamic modeling

The hydrodynamic model ANUGA (Rigby and van Drie, 2008) was used to simulate the generation and routing of flow for September 9-13, 2013 within five catchments along the Colorado Front Range.

- Computes 2-D Shallow Water equation for all cells, not differentiating channels and hillslopes
- Allows for rapidly varying flow depth and velocity (unsteady flow)
- Preserves steep wave fronts (as in the leading edge of flash floods)

Topography grids were created from 10 m DEMs with three zones of varying resolution within each basin, with the highest point density along the channels and the foothills. Runoff was generated using the hourly rainfall accumulation maps.

The values of stage and flow momentum in x and y directions were recorded every 30 minutes of model time. These were used to find the discharge at the location of each streamgage as well as the potential magnitude of sediment transport throughout the steam network.

Other technical details:
- Python, with computationally intensive components in C
- Finite-volume Godunov-type (*Toro*,1992) central-upwind scheme (*Kurganov et al.*, 2001)
- Explicit Euler method with variable timesteps
- Unstructured triangular grid
- Open source (GNU GPL)

Results

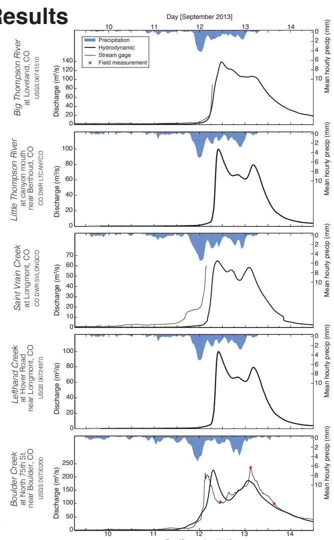


Figure 4: Predicted hydrographs found with the hydrodynamic model (thick black line), and **observed streamflow** from available gage record (thin black line) at the location of five streamflow gaging stations within the study area, in cubic meters per second. Red stars show field measurements of discharge collected by the USGS. Blue filled curve shows the mean hourly precipitation within the contributing area of each gage, in mm/hr.

Results (cont.)

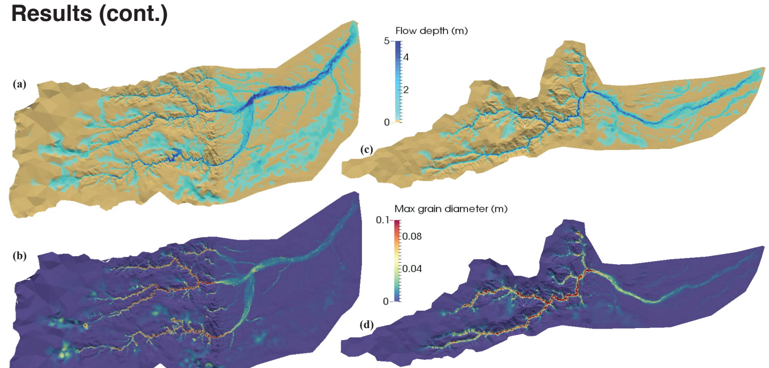


Figure 5: Simulation results of the 2013 Front Range flood on **Boulder Creek (left) and Lefthand Creek (right) for September 12 at 4:00 PM.** (Top) Flow depth, (Bottom) Maximum transportable grain size, obtained from the shear stress that the flow could impart on the bed given the flow depth and momentum predicted by the hydrodynamic model.

Scan to access videos of these simulations

For small basins, the hydrodynamic model predicted peak discharges that were higher than the gage observations and hydrographs with steeper limbs and more short-term variability. The shape of the model hydrograph better predicted the records in increasingly large drainage areas, but the arrival time of the peak flow lagged by up to six hours at the gages far downstream.

Hillslopes and channels at elevations between 1700 m and 2500 m experienced higher magnitudes of shear stress than the landscape elsewhere. The greatest values were along the trunk streams and largest tributaries within this elevation window.

The first period of intense precipitation (afternoon of September 11) brought a rapid increase in shear stress at mid elevations and along the trunk streams east of the range front. This shift was gradual across the Big Thompson, Little Thompson, and Saint Vrain basins, and along the channels of Boulder Creek and South Boulder Creek. There, the magnitude of shear stress remained roughly steady until midday of September 13, when it began to decrease gradually.

In constrast, the shifts in the magnitude of shear stress in mid-elevation tributaries within the Boulder Creek basin and all channels in the Lefthand Creek were sudden and propagated down the stream network.

East of the range front, Little Thompson, Lefthand and Boulder creeks saw two periods of heightened shear stress that coincided with increased rainfall intensity in the basins, while Big Thompson showed little variability in maximum shear stress for the duration of the flood.

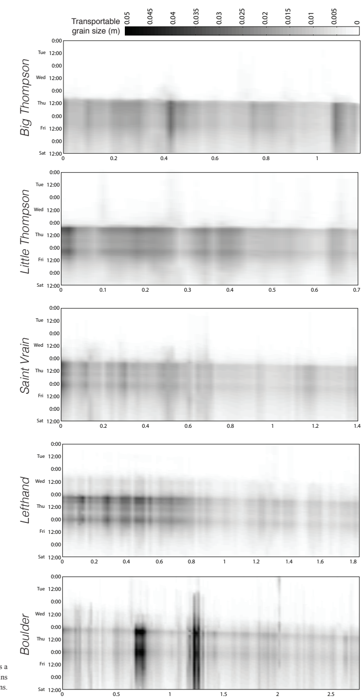


Figure 6: Maximum transportable grain size along the main channel of each watershed, in mm (color gradient) as a function of distance from the range front (horizontal axis) and time (vertical axis). Darker colors indicate that larger grains could have been mobile. Dark vertical streaks are artifacts of the calculations at tributary junctions.

Discussion and Conclusion

In the Front Range of Colorado, climate varies rapidly with elevation, generating strong gradients of precipitation and thus variability in the timing and magnitude of runoff generation across short distances.

Extreme rainfall events, such as the storm that caused the 2013 Front Range flood, magnify the effects that catchment size and mean elevation have on the geomorphic response of different areas of the landscape. These simulations indicate that small basins responded more episodically to the storm, triggering multiple pulses of flow with high shear stresses and a high potential for transport. Larger basins, on the other hand, dampened the fluctuating inputs of their subcatchments and generated powerful but steady flows.

These findings suggest that, during widespread and intense precipitation events, small basins such as Lefthand Creek and Little Thompson Creek will be capable of supplying sediment to the plains of comparable or larger size than larger watersheds. We speculate that this results from the rapid response of these basins to intense rainfall, which results in "flashier" flows at their outlets.

The disparate response of catchments to this extreme rainfall event suggests that individual points in the landscape might evolve in response to processes with different recurrence intervals and degrees of effectiveness. While larger streams might be gradually shaped by frequent, low magnitude floods, the smallest basins might go through long periods of minimal activity interspersed with pulses of erosion at rates that are higher than the long-term rates for the landscape as a whole.