Modeling hydrologic and erosional responses of landscapes to fire using the Landlab modeling environment

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I. Overview

Landscape response to fire has been well documented in field observations, but the long-term geomorphic and hydrologic effects beyond a single fire are not well understood. The utilization of models to understand this response through time is critical, as significant erosion events post-fire could potentially disrupt steady-state landscapes and affect both short and long-term landscape evolution.

To understand and quantify landscape response to fire across multiple time scales, the Landlab modeling environment can be used to explore morphological impacts of erosion events post-fire. Landlab is a highly flexible plug-and-play modeling framework that links together digital elevation model (DEM)-based grids, stochastic storm generators as well as an overland flow component that can simulate scenarios that may cause large flow or erosion events in the first post-fire year.

Parameters in the components are drawn from the existing post-fire literature and are applied across two grids, each of which represents a burned watershed: the Spring Creek watershed, Colorado, burned in the 1996 Buffalo Creek Fire and a site in the Chiricahua Mountains, Arizona, burned in the 2011 Horseshoe 2 Fire.

Both sites were affected by similar intensity storms (I_{30} = 72 mm/hr) post-fire but experienced different erosional and hydrological responses. This scenario is run across both sites in order to validate Landlab's suitability for post-fire modeling.

Figure 1: Photos depicting changes in sediment clast movement before, during and after a high-intensity post-fire precipitation event in the Chircahua Mountains in southeastern Arizona.

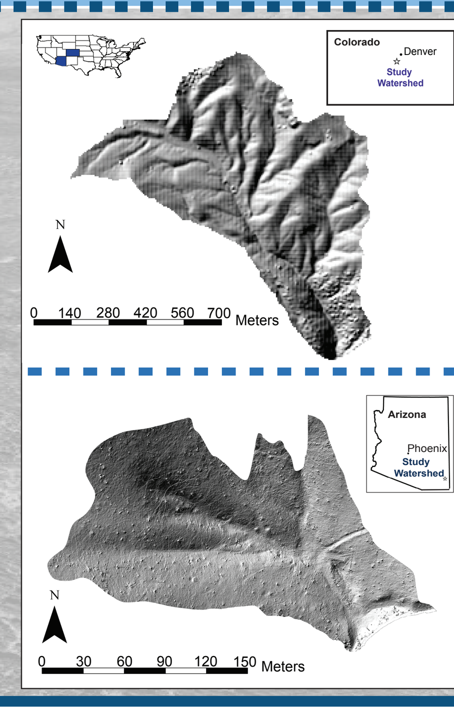
II. Study Areas

Spring Creek Watershed

During the 1996 Buffalo Creek Fire, several thousand acres of forest burned throughout the Buffalo Creek and Spring Creek watersheds.

On July 12, 1996, an high-intensity rainstorm (**I_{30} = 72 mm/hr**) initiated extensive flooding and fluvial erosion throughout the entire watershed.

This study examines the impact of that storm throughout a 600 m^2 subwatershed contained within the Spring Creek watershed, using a 5 m DEM.



Chiricahua Watershed

In the summer of 2011, the Horseshoe 2 Fire became one of the largest fires in Arizona state history, burning approximately 900 km^2 of forest.

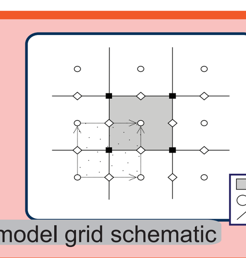
On July 11, 2011, a high-intensity rainstorm (**I_{30} = 72.4 mm/hr**) initiated significant flooding throughout the watershed. Repeat surveys estimated ~600 m^3 sediment moved during this event.

The impact of this storm is tested across a 1 m DEM of the 27,000 m^2 watershed.

III. Landlab Post-fire Model

Driver
1. Import data
2. Instantiate grid
3. Initialize components
4. Initialize variables
5. Components operate on grid
6. Components output variables
7. Visualize output
8. Export data

Grid
Read in DEM
Create raster grid



Landlab raster model grid schematic

Data Structures
Data stored at nodes:
Water depth (m)
Shear stress (Pa)
Data stored at links:
Discharge (m^3/s)

Components
1. Rainfall generator
2. Overland runoff and discharge generator

IV. Model Math and Parameters

Discharge changes over time as flow is routed across the watershed. Water depths and shear stress are calculated at grid nodes, while discharge is calculated at the link between the study node and the node in the direction of steepest descent.

$$q_{t+1} = \frac{q_t - gh_t\Delta t \frac{\partial(h_t+z)}{\partial x}}{(1 + gh_t\,\Delta t n^2 q_t / h_t^{10/3})}$$

Based on Bates et al., (2010)

Table 1: Grid Characteristics

	Chiricahua	Spring Creek
Interior Nodes	29746	24899
Active Links	58888	49296
Total Run Time (minutes)	216	138

Storm Duration (hr)	Storm Intensity (mm/hr)	Model Run Time (hr)
1.63	33.18	1.63

Table 2: Precipitation Parameters for both simulations

V. Spring Creek Results

The overland flow regime in Landlab calculates water surface slope, water depth, discharge and shear stress at each time step in the model run.

The model generates a flow network with a hydrograph that reaches steady state at all points in the Spring Creek watershed.

Shear stress values nearing ~ 100 Pascals in conditions where water depths exceed tens of centimeters could entrain gravel and cobble-sized clasts up to 63.5 millimeters in diameter, significant for this ephemeral tributary.

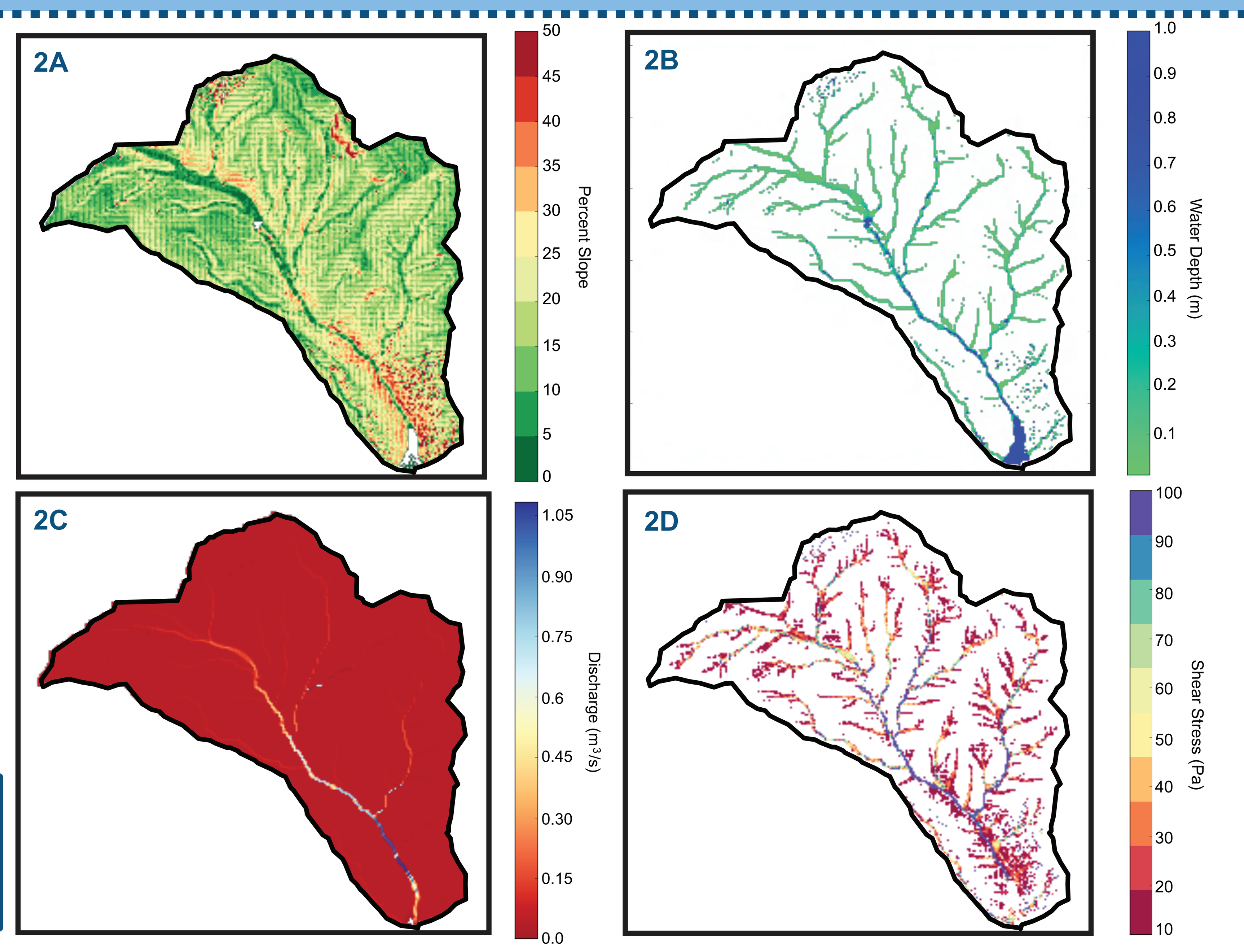


Figure 2: Results of the Spring Creek, Colorado run. Plots show (A) water surface slope, (B) water depths, (C) discharge and (D) shear stress values throughout the watershed at one time during the modeled precipitation event.

VI. Chiricahua Results

Instead of the strongly networked system seen in the Spring Creek, Colorado run, the simulated precipitation event drove flow in one wide channel with water ponding in the roadside culvert.

Discharge, depth and shear stress values throughout the modeled storm were less than those seen in the Spring Creek run, but could still entrain gravel-sized particles up to 30 millimeters in diameter, again, significant as this small watershed is also ephemeral.

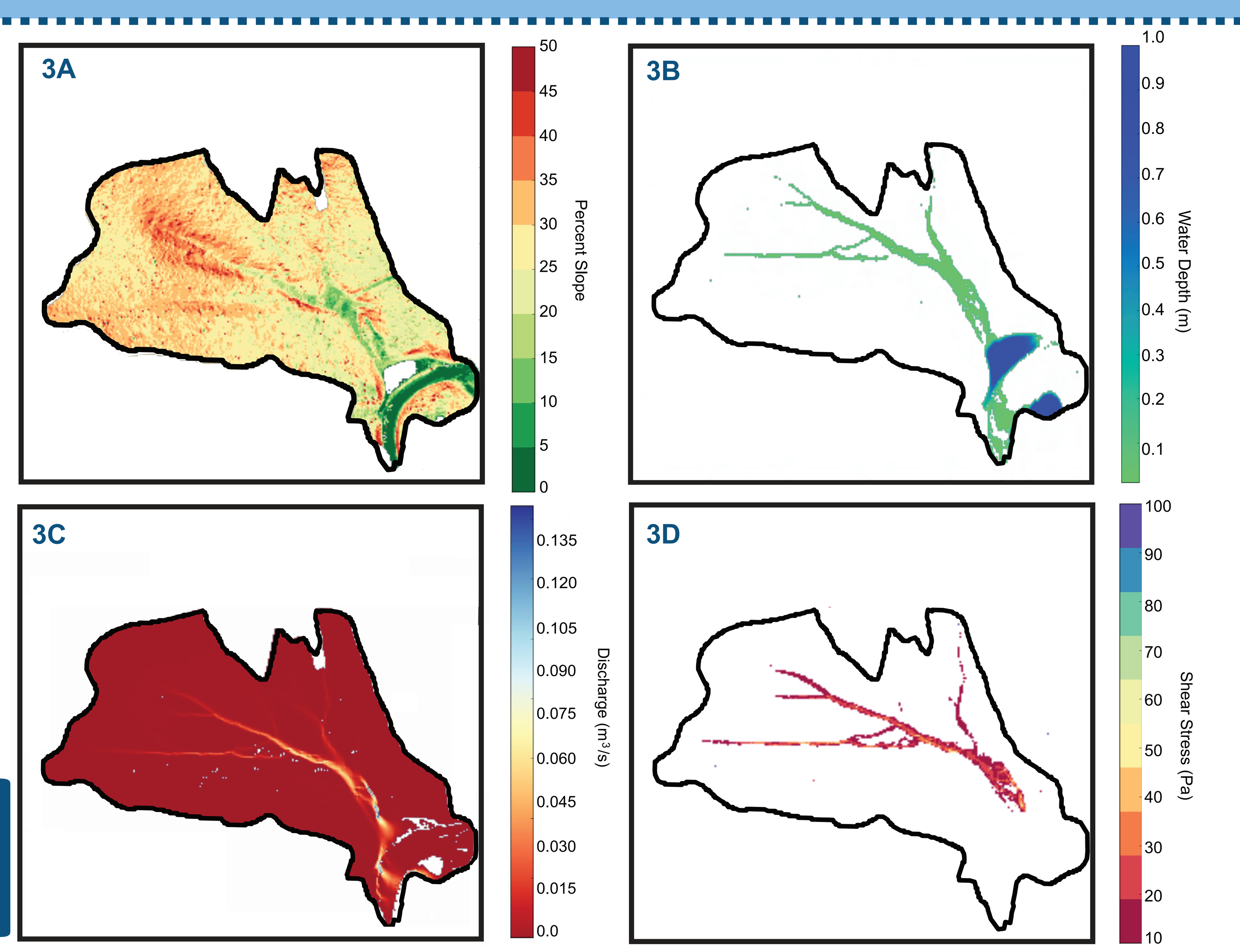


Figure 3: Results of the Chiricahua, Arizona run. Plots show (A) water surface slope, (B) water depths, (C) discharge and (D) shear stress values throughout the watershed at one time during the modeled precipitation event.

VII. Conclusions

The Landlab modeling environment can simulate hydrologic behavior across a landscape by coupling DEM data with precipitation and overland flow components.

These two simulations show that while both watersheds were affected by similar precipitation events, hydrologic responses varied.

DEM resolution does seem to affect the speed of model runs and will be addressed in future Landlab development.

VIII. Future Work

Validate these findings against discharge data collected during comparable precipitation events.

Test differences in infiltration rate as a proxy for post-fire hydrophobic soil conditions.

Create and validate a sediment transport component in the Landlab modeling environment.

Incorporate existing ecohydrology Landlab components, such as soil moisture and vegetation.

Reference

Bates, Paul D., Matthew S. Horrit and Timothy J. Fewtrell. "A simple inertial formulation of the shallow water equations for efficient two-dimensional flood inundation modelling." Journal of Hydrology, 2010. 387:33-45.

Acknowledgements

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Check out Landlab!