Cellular automata modeling of flow-vegetation-sediment interactions in low-energy environments

Laurel Larsen, UC Berkeley (laurel@berkeley.edu)

1. Introduction and Hypothesis

Numerical simulations provide powerful tools for examining the sensitivity of landscape structure to environmental drivers and testing hypotheses about the mechanisms responsible for evolution of a particular morphology. However, model development to address fundamental geomorphic questions about low-gradient floodplains and wetlands, where flow-vegetation feedbacks are strong, has been limited. Historically, model development for these landscapes has been restricted by limited understanding of the physics of flow through vegetation. Work within the past decade, however, (e.g., Nepf 1999; Lightbody and Nepf 2004,2006) has vastly improved our ability to simulate flow through vegetation canopies at fine scales. Challenges remain in extending those capabilities over the landscape scale to evaluate emergent effects resulting from flow-vegetation-sediment interactions.

Here I describe a hierarchical, cellular automata modeling approach for realistically simulating flow, sediment transport, and landscape evolution in low-energy floodplains and wetlands. This modeling strategy is ideally suited to addressing fundamental and applied questions in low-gradient geomorphology:

1. What causes parallel-drainage wetlands to achieve millennial-timescale stability (top right), and why has this morphology catastrophically declined in the Everglades over the past century?

2. Under what conditions is a complex, multithreaded stream-wet meadow system a stable configuration, rather than a single-threaded, incised stream (bottom and middle right)? What causes shifts between these morphologies?

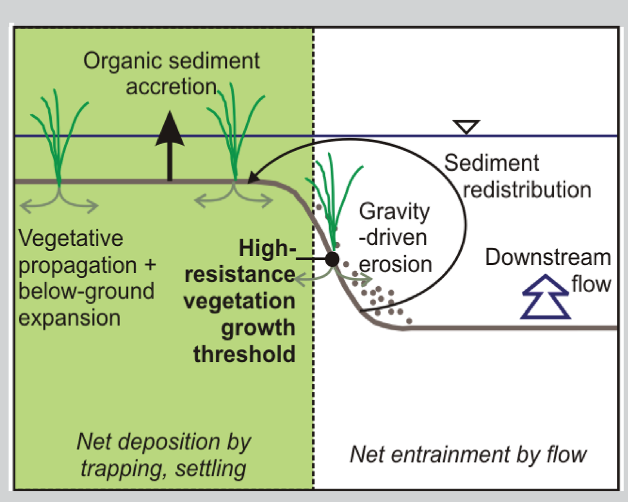
Hypothesis:
In the Everglades, the model was used to test the hypothesis (Larsen et al. 2007) that sediment redistribution by flow, as impacted by the large-scale flow routing around ridges, results in a sediment balance at ridge edges that ultimately prevents ridges from further spreading.

A relatively well-preserved portion of the Everglades ridge and slough landscape. Peat ridges, which appear green, are elevated just 10-20 cm above sloughs and are inundated for much of the year. Ridges are elongated parallel to the direction of water flow.

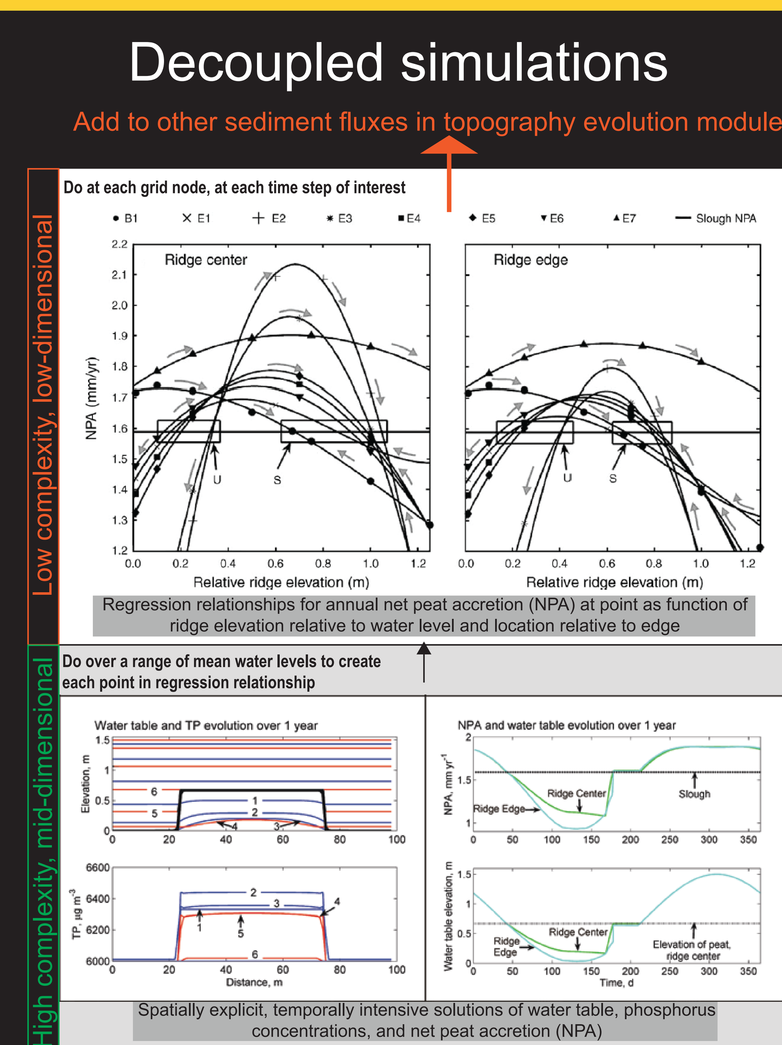
Big Spring Run, PA, prior to a restoration in 2011 that changed the morphology of the channel. The single-threaded, incised morphology here is ubiquitous throughout today's eastern Piedmont province. Photo: Michael Rahnis

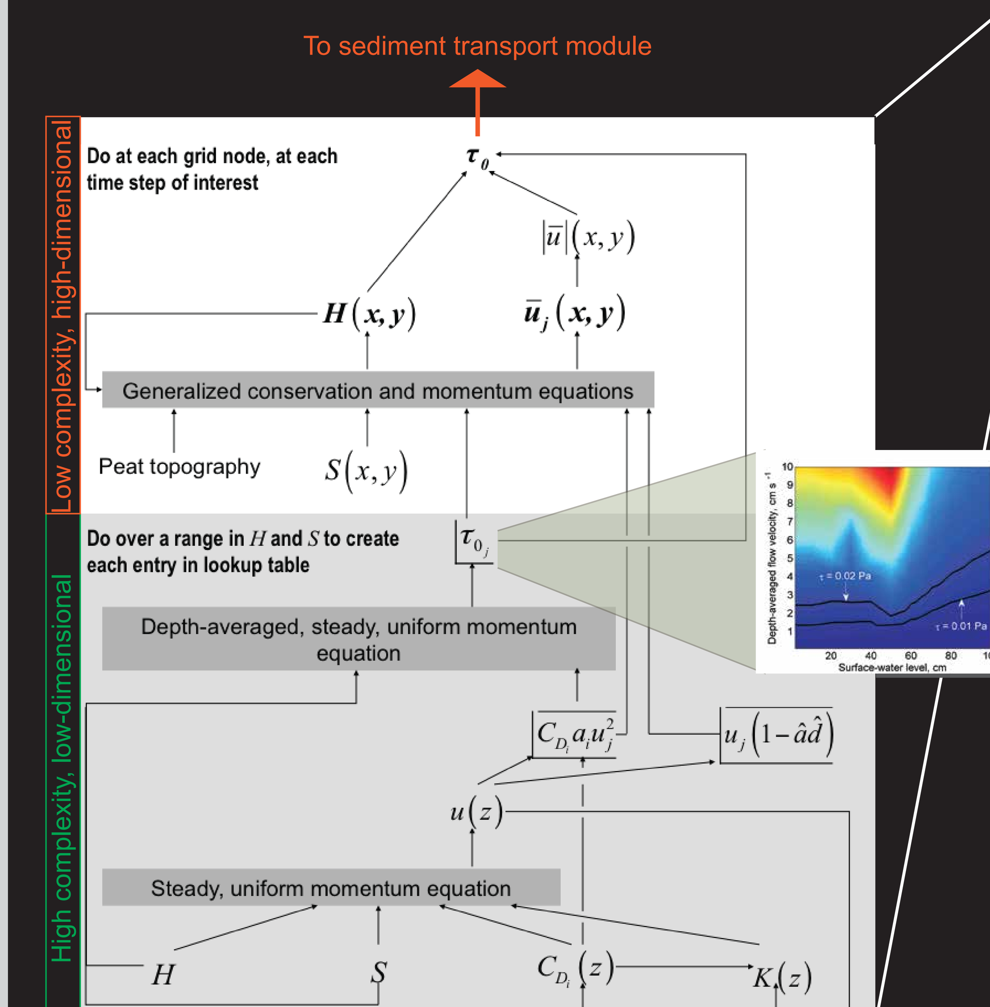
Big Spring Run post-restoration. The complex, wet-meadow morphology depicted here is thought to be the dominant morphology for Piedmont streams prior to widespread construction of mill dams in the Colonial period (Walter and Merritts, 2008). Photo: Michael Rahnis

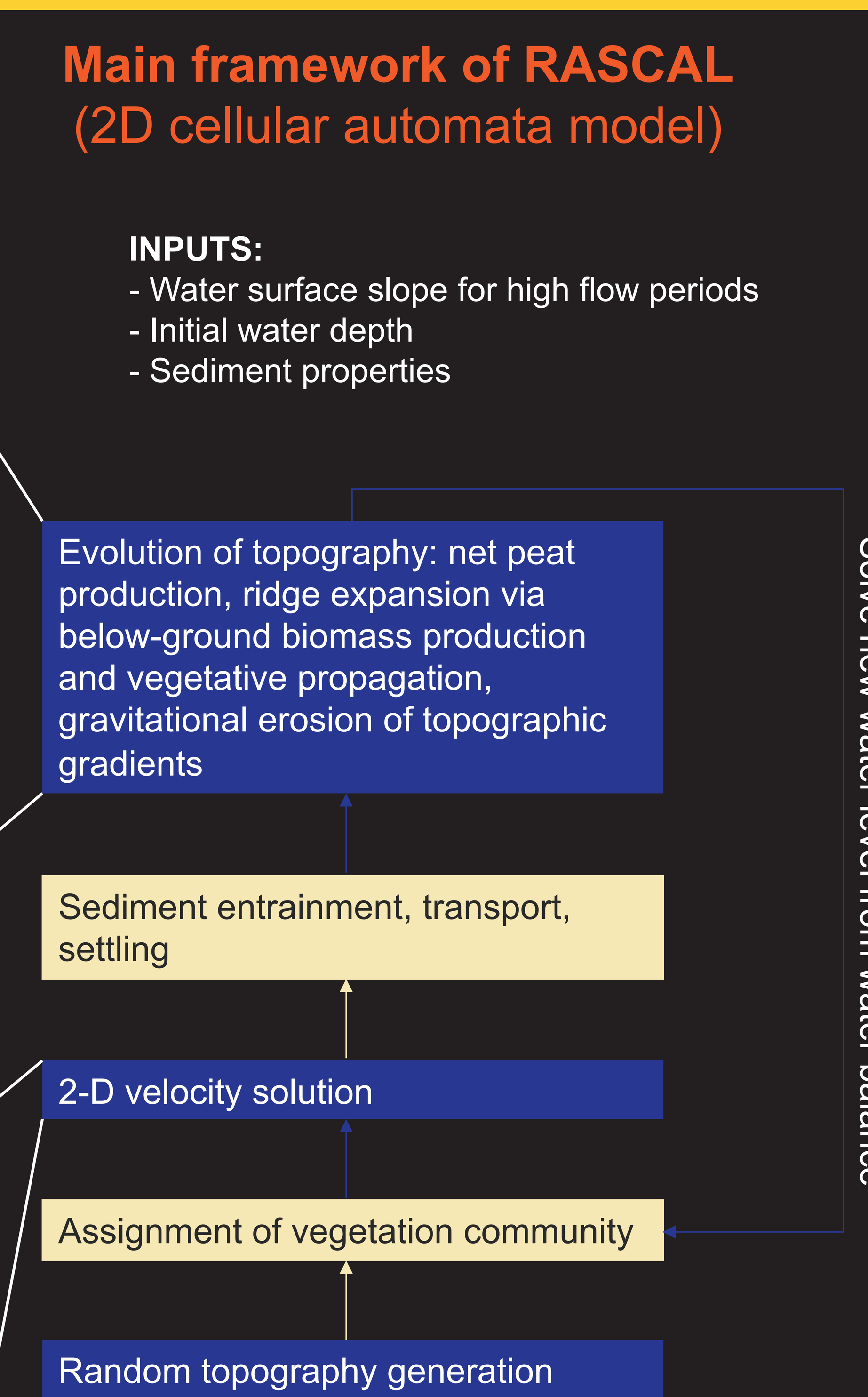
The "sediment redistribtion hypothesis": A mechanism proposed to prevent ridges from indefinite expansion into sloughs. In the absence of flow, ridges tend to expand because of vegetative propagation, efficient in situ production of peat arising from the imbalance between primary production and decomposition, and gravitational movement of loosely consolidated, flocculaent organic sediment. However, when ridges widen across the landscape, flow into sloughs becomes more channelized and ableto induce erosion at slough margins. Ridges acheive lateral stability when that erosion balances sediment addition processes.



2. Hierarchical Modeling Approach







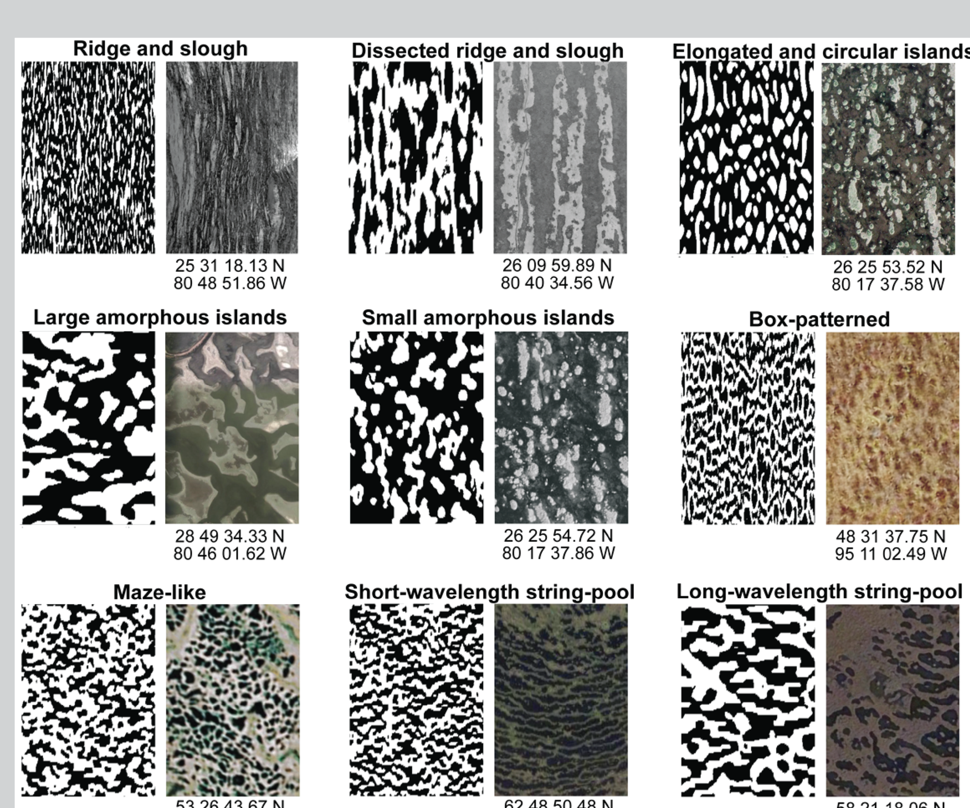
PROBLEM: Subtle spatial differences in flow velocity, bed shear stress, and peat accretion have a big impact on landscape patterning in low-gradient, vegetated flows. The model needed to be accurate enough to capture these subtleties, yet efficient enough to run over spatial domains of tens of kilometers and over millennial timescales.

SOLUTION: A cellular automata modeling approach was selected for the main landscape model, RASCAL (Ridge And Slough Cellular Automata Landscape). However, more detailed spatial and temporal dynamics were incorporated hierarchically through decoupled models whose results were not dependent on or were only weakly dependent on the large-scale dynamics. Results of these models were summarized as lookup tables (denoted by half-boxes around variables to the left and depicted in the inset) or as simple regression functions.

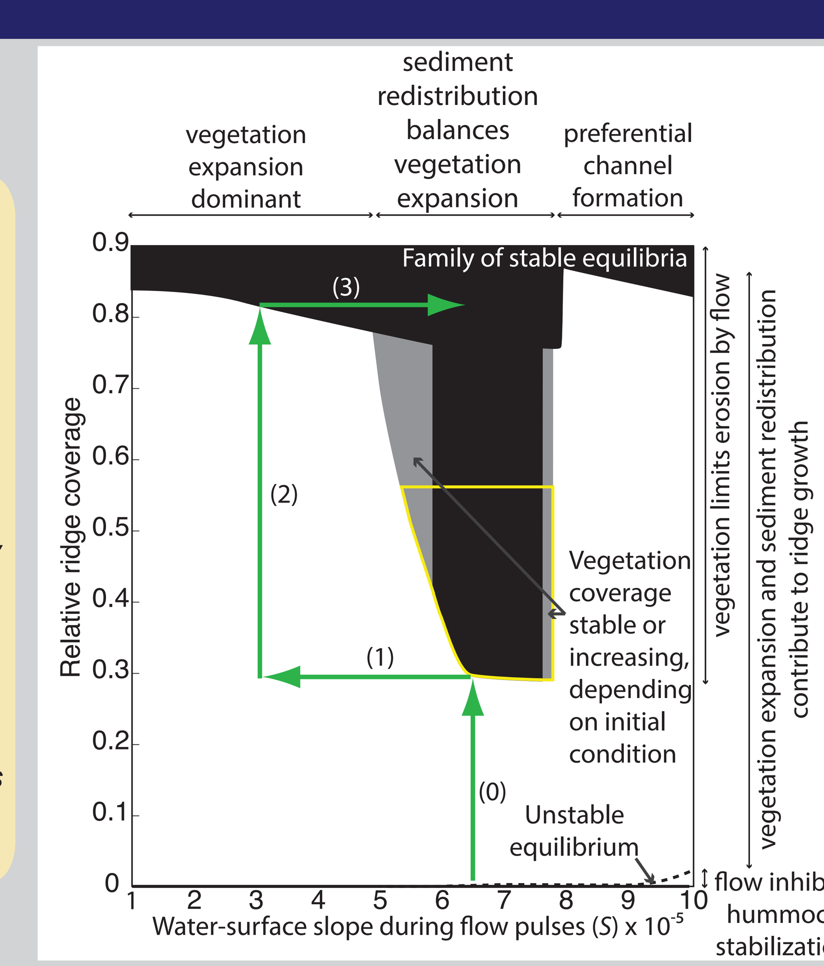
3. Results

Because of RASCAL's simplicity and computational efficiency, it was possible to conduct a global sensitivity analysis over the plausible range of model input parameters, using space-filling Latin hypercube sampling. Certain combinations of model parameters produced realistic parallel drainage landscapes (Larsen and Harvey 2010). Statistical tests revealed that water surface slope was one of the most sensitive parameters, and a bifurcation analysis (right) suggested that low-gradient parallel drainage landscapes occur over just a narrow range of water surface slopes. Over other ranges of environmental variables, flow-vegetation-sediment feedbacks produce a range of other landscape patterns similar to those found in diverse floodplains and wetlands throughout the world (Larsen and Harvey 2011).

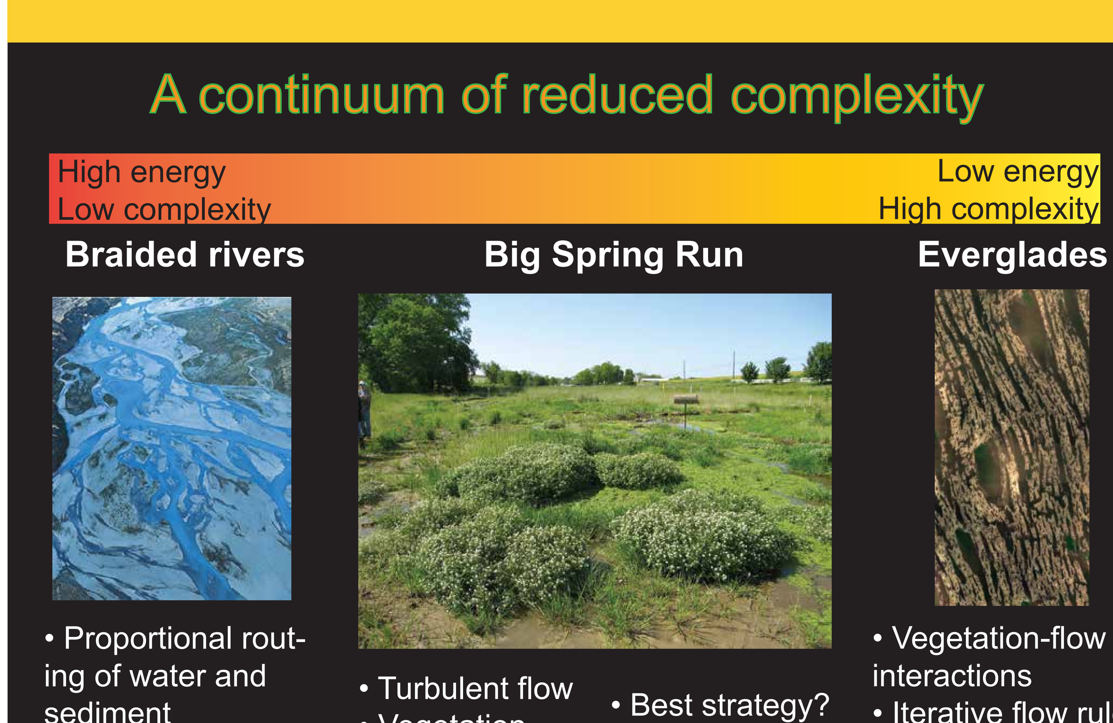
RASCAL model outputs for different combinations of model input parameters, compared to Google Earth images of floodplain/wetland landscape pattern.



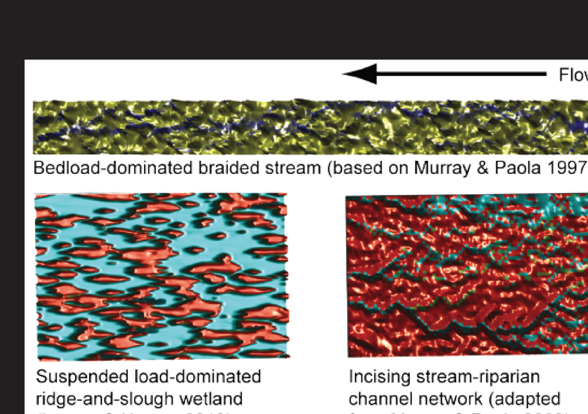
Bifurcation diagram, showing stability of different ridge coverages as a function of water-surface slope. White areas are unstable; black areas are families of stable equilibria. Gray areas are conditionally stable, depending on the direction from which they were approached. The area outlined in yellow denotes parallel-drainage landscapes with broad ridges and sloughs. Green arrows show the trajectory of Everglades landscape evolution, from formation (0), to levee construction (1), which caused landscape degradation (2). Proposed restoration efforts focused on flow releases (3) may follow the dashed trajectory if not accompanied by measures to remove sawgrass from sloughs (e.g., drowning).



4. Current Challenges



Current work focuses on hybridizing reduced-complexity modeling approaches that simulate the evolution of turbulent flow systems with those that simulate low-energy systems governed by flow through vegetation. This work will produce new tools for testing hypotheses about the evolution and stability of wet meadow systems like Big Spring Run and lead to a greater understanding of floodplain geomorphology in general.



3D visualization of outputs of cellular landscape models with different rules. Images use a false-color scheme in which red represents vegetation.

5. Acknowledgements and References

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