Dynamic Landscape Evolution

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Abstract

This is a fine-scale, short term, process-based landscape evolution model using simulated erosion and deposition to generate a timeseries of digital elevation models. This model uses a path sampling method to solve water and sediment flow continuity equations and model mass flows over complex topographies based on topographic, land cover, soil, and rainfall parameters. This either steady state or dynamic model can simulate landscape evolution for a range of hydrologic soil erosion regimes.

Keywords: landscape evolution, dynamic model

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1. Introduction

This process-based, spatial distributed, dynamic model uses a path sampling method to solve the water and sediment flow equations [2] and model mass flows over complex topographies based on topographic, land cover, soil, and rainfall parameters. The modeled flow of sediment – a function of the flow of water, soil detachment, and transport parameters – is then used to estimate the net erosion and deposition rates and the associated short-term evolution of the topography.

1.1. Literature review
Steady state versus dynamic flows

Spatial and temporal scales

Table of landscape evolution models

1.2. Conceptual model
2. Erosion-deposition model

2.1. Shallow water flow
We simulated shallow overland water flow controlled by spatially variable topography, soil, landcover, and rainfall parameters using the SIMWE model to solve the continuity and momentum equations for steady state water flow with a path sampling method. Shallow water flow can be approximated by the bivariate form of the St Venant equation:

$$\frac{\partial h(\mathbf{r}, t)}{\partial t} = i_e(\mathbf{r}, t) - \nabla \cdot \mathbf{q}(\mathbf{r}, t) \tag{1}$$

where:

$\mathbf{r}(x, y)$ is the position [m]
t is the time [s]
$h(\mathbf{r}, t)$ is the depth of overland flow [m]
$i_e(\mathbf{r}, t)$ is the rainfall excess [m/s]
(rainfall − infiltration − vegetation intercept)
$\mathbf{q}(\mathbf{r}, t)$ is the water flow per unit width [m^2/s].

By integrating a diffusion term $\propto \nabla^2[h^{5/3}(\mathbf{r})]$ into the solution of the continuity and momentum equations for steady state water flow diffusive wave effects can be approximated so that water can flow through depressions.

$$-\frac{\varepsilon(\mathbf{r})}{2}\nabla^2[h^{5/3}(\mathbf{r})] + \nabla \cdot [h(\mathbf{r})\mathbf{v}(\mathbf{r})] = i_e(\mathbf{r}) \tag{2}$$

where:

$\varepsilon(\mathbf{r})$ is a spatially variable diffusion coefficient.
This equation is solved using a Green's function Monte Carlo path sampling method [2].

2.2. Erosion-deposition
Steady state sediment flow equation with diffusion...

$$... \tag{3}$$

2.3. Landscape evolution

$$\Delta z(x, y, t) = \Delta t \cdot d_s(x, y, t) \cdot \rho_s^{-1} \tag{4}$$

where:
Δz = change in elevation (m)
d_s = net erosion-deposition ($kg\ m^{-2}s^{-1}$)
ρ_s = sediment mass density ($kg\ m^{-3}$)

... [1]

2.4. Gravitational diffusion

$$\Delta z(x, y, t) = \Delta t \cdot \rho_s^{-1} \cdot \varepsilon_g \cdot div(x, y, t) \tag{5}$$

where:
Δz = change in elevation (m)
ρ_s = sediment mass density ($kg\ m^{-3}$)
ε_g = gravitational diffusion coefficient ($m^{-2}s^{-1}$)
div = divergence (m^{-1})

... [?]

3. Detachment limited model

3.1. Shallow water flow

3.2. Sediment flow

$$\Delta z(x, y, t) = \Delta t \cdot q_s(x, y, t) \cdot \varrho(r)^{-1} \tag{6}$$

where:
Δz = change in elevation (m)
q_s = sediment flux ($kg \cdot m^{-1}s^{-1}$)
ϱ = mass of water carried sediment per unit area ($kg \cdot m^{-2}$)

... [1]

3.3. Landscape evolution

$$\Delta z(x, y, t) = \Delta t \cdot q_s(x, y, t) \cdot \varrho_s^{-1} \qquad (7)$$

where:
Δz = change in elevation (m)
q_s = sediment flux ($kg \cdot m^{-1} s^{-1}$)
ϱ = mass of water carried sediment per unit area ($kg \cdot m^{-2}$)

... [1]

3.4. Gravitational diffusion
4. Transport limited model

4.1. Unit stream power erosion deposition

4.2. Landscape evolution

4.3. Gravitational diffusion

5. Implementation

This set of python scripts is available on Github at `https://github.com/baharmon/landscape_evolution` released under the GNU General Public License version 2. These scripts are meant to be run inside of GRASS GIS using the GRASS Python Scripting Library. GRASS GIS is an open source project released under the GNU General Public License version 2. GRASS GIS is available at `https://grass.osgeo.org/`.

6. Case study

Study area.

6.1. Comparison of r.evolution, r.land.evol, r.terradyn
7. Tangible landscape evolution

Tangible Landscape – a tangible user interface tightly integrated with a geographic information system for intuitively sketching in 3D [3]. Conceptually, Tangible Landscape couples a physical model with a digital model in a real-time feedback cycle of 3D scanning, geospatial modeling and simulation, and projection in order to physically manifest digital data as tangible bits. With tangible bits users can directly, physically feel and manipulate data with their bodies – naturally, intuitively understanding space, form, and process. Tangible Landscape is available on Github at `https://github.com/ncsu-osgeorel/grass-tangible-landscape`.

We coupled Tangible Landscape with the landscape evolution model to test the model and experiment with strategies for restoration. We used Tangible Landscape to computationally steer the landscape evolution model and interactively explore the relationship between overland flow patterns and changes in topography. By manually changing the physical model of the landscape we change the topography used by the model.

8. Discussion

8.1. Future work

1. Test the model on historical data

2. Test the model with UAS Sfm time-series

3. Implement as a Tangible Landscape analysis

4. Live, in-situ fabrication in polymer-enriched sand with a robotic arm

9. Conclusion

Appendix A. Supporting information

Appendix A.1. Code
Github repository

Appendix A.2. Data
GRASS GIS Mapset

Appendix A.3. 3D models
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Appendix A.4. Tangible Landscape
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References

[1] Mitasova, H., Barton, M., Ullah, I., Hofierka, J., Harmon, R., 2013. 3.9 GIS-Based Soil Erosion Modeling. In: Shroder, J. F. (Ed.), Treatise on Geomorphology. Elsevier, San Diego, California, USA, Ch. 3.9, pp. 228–258.
URL http://www.sciencedirect.com/science/article/pii/B978012374739600052X
[2] Mitasova, H., Thaxton, C., Hofierka, J., McLaughlin, R., Moore, A., Mitas, L., 2004. Path sampling method for modeling overland water flow, sediment transport, and short term terrain evolution in Open Source GIS. Developments in Water Science 55, 1479–1490.
[3] Petrasova, A., Harmon, B., Petras, V., Mitasova, H., 2015. Tangible Modeling with Open Source GIS. Springer.

Figure 1: **Rapid prototyping.** 3-axis CNC fabrication of the evolved landscape in polymer-enriched sand using a plunge cut.