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 time-series of digital elevation models and compute the net change in elevation. 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

Contents

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1. Introduction

This process-based, spatially 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 and 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.

This highly adaptable model can simulate landscape evolution for different soil erosion regimes across a range of spatiotemporal scales using either the simulated water erosion (SIMWE) model, the unit stream power erosion deposition (USPED) model, or the 3-dimensional revised universal soil loss equation (RUSLE 3D) model.

This model has been implemented as an add-on module for a free, open-source geographic information system (GIS) – GRASS GIS. It supports multithreading and parallel processing for the efficient computation of physics-based simulations for large, high resolution topographic datasets.

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:

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

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.

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

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...

$$... \qquad (3)$$

2.3. Landscape evolution

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

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

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

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*

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

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

5. Unit stream power erosion deposition model

5.1. *Unit stream power erosion deposition*

5.2. *Landscape evolution*

5.3. *Gravitational diffusion*

6. Revised universal soil loss equation 3D model

6.1. Revised universal soil loss equation

Event-based r-factor derivation. [?]

$$e_r = 0.29 \cdot (1. - 0.72 \cdot exp(-0.05 \cdot i_r)) \tag{8}$$

where:
e_r = unit rain energy ($MJ \cdot ha^{-1} \cdot mm^{-}1$)
i_r = rainfall intensity ($mm \cdot h^{-1}$)

$$v_r = i_r \cdot t_r \tag{9}$$

where:
v_r = rainfall volume (mm)
i_r = rainfall intensity ($mm \cdot h^{-1}$)
t_r = time interval (h^{-1})

$$r = e_r \cdot v_r \cdot i_r \tag{10}$$

where:
r = erosivity index ($MJ \cdot mm \cdot ha^{-1} \cdot hr^{-1} \cdot s^{-}1$)
e_r = unit rain energy ($MJ \cdot ha^{-1} \cdot mm^{-}1$)
v_r = rainfall volume (mm)
i_r = rainfall intensity ($mm \cdot h^{-1}$)

3D topographic factor.

$$ls(x, y) = (m + 1.0) \cdot (a(x, y) \cdot a_0^{-1})^m \cdot (sin(\beta)/\beta_0)^n \tag{11}$$

where:
ls = a dimensionless topographic (length-slope) factor
a = water flow accumulation (m)
a_0 = length of the standard USLE plot ($22.1m$)
β = slope angle (°)
m = empirical coefficient
n = empirical coefficient
β_0 = slope of the standard USLE plot (0.09°)
[?]

Revised universal soil loss equation.

$$e = r \cdot k \cdot ls \cdot c \cdot p \tag{12}$$

where:
e = soil loss ($kg \cdot m^{-2} \cdot min^{-1}$)
r = erosivity factor ($MJ \cdot mm \cdot ha^{-1} \cdot hr^{-1} \cdot s^{-}1$)
k = soil erodibility factor ($ton \cdot ha \cdot hr \cdot ha^{-1} \cdot MJ^{-1} \cdot mm^{-1}$)
ls = dimensionless topographic (length-slope) factor
c = dimensionless land cover factor
p = dimensionless prevention measures factor

6.2. Landscape evolution

6.3. Gravitational diffusion

7. Implementation

The GRASS GIS add-on module written in Python is available on Github at `https://github.com/baharmon/landscape_evolution` released under the GNU General Public License version 2. 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/`.

8. Case study

8.1. Fort Bragg

8.2. Patterson Branch Creek

8.3. Benchmarks

9. 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.

10. Discussion

10.1. 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

11. 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

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