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r.sim.terrain: a dynamic landscape evolution model

Brendan Alexander Harmon[1,2], Helena Mitasova[1,3], Anna Petrasova[1,3], and Vaclav Petras[1,3]

[1]Center for Geospatial Analytics, North Carolina State University, Raleigh, North Carolina, United States of America
[2]Robert Reich School of Landscape Architecture, Louisiana State University, Baton Rouge, Louisiana
[3]Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, North Carolina, United States of America

Correspondence: Brendan Harmon (brendan.harmon@gmail.com)

Abstract. While there are numerical landscape evolution models that simulate how steady state flows of water and sediment reshape topography over long periods of time, this is the first to simulate short-term topographic change for both steady state and dynamic flow regimes. It is a process-based, spatially distributed model that uses the water and sediment flow continuity equations to simulate how overland sediment mass flows reshape topography. This either steady state or dynamic model can simulate how topography will evolve for a range of hydrologic soil erosion regimes based on topographic, land cover, soil, and rainfall parameters. A case study demonstrates how the behavior and results of the dynamic model differ the steady state model. The dynamic model is more accurate and demonstrates cross-scale interactions between topographic form and sediment flow processes.

Copyright statement. ...

1 Introduction

Landscape evolution models represent how the surface of the earth changes over time. Most studies of landscape evolution have been descriptive, but a number of numerical landscape evolution models have been developed that simulate elevational change over time **?**. Numerical landscape evolution models such as the Channel-Hillslope Integrated Landscape Development (CHILD) model **?** and SIBERIA **?** simulate steady state flows over long temporal scales. Landlab, [1] a new Python library for numerically modeling Earth surface processes **?**, has components for simulating landscape evolution such as the Stream Power with Alluvium Conservation and Entrainment (SPACE) model **?**. There are still, however, major research questions to address in the theoretical foundations of erosion modeling such as how erosional processes scale over time and space and how sediment detachment and transport interact **?**. A dynamic landscape evolution model is needed to study fine-scale spatial and short-term temporal erosional processes such as gully formation and the development of microtopography. While most numerical landscape evolution models simulate peak flows at steady state (see Table 2), short-term erosional processes like

[1]http://landlab.github.io/

gully formation can be dynamic with significant morphological changes happening within minutes before flows reach steady state.

At the beginning of a rainfall event the overland water flow regime is dynamic – its depth changes at a variable rate over time and space. If the intensity of rainfall continues to change throughout the event then the flow regime will remain dynamic. If, however, the overland flow reaches a peak rate then the hydrologic regime is considered to be at steady state. At steady state:

$$\frac{\partial h(x,y,t)}{\partial t} = 0 \tag{1}$$

where:

(x,y) is the position (m)

t is the time (s)

$h(x,y,t)$ is the depth of overland flow (m)

Gullies are eroded, steep banked channels formed by ephemeral, concentrated flows of water. A gully forms when overland waterflow converges in a knickzone – a concave space with steeper slopes than its surroundings – during intense rainfall events. When the force of the water flow concentrated in the knickzone is enough to detach and transport large amounts of sediment, an incision begins to form at the apex of the knickzone – the knickpoint or headwall. As erosion continues the knickpoint begins to migrate upslope and the nascent gully channel widens, forming steep channel banks. Multiple incisions initiated by different knickpoints may merge into a gully channel and multiple channels may merge into a branching gully system. This erosive process is dynamic; the morphological changes drive further changes in a positive feedback loop until water flow reaches steady state. When the gully initially forms the soil erosion regime should be detachment capacity limited with the concentrated flow of water in the channel of the gully detaching large amounts of sediment and transporting it to the foot of the gully, potentially forming a depositional fan. After the initial formation of the gully the soil erosion regime may change. If the intensity of the rainfall decreases the regime may switch to erosion-deposition. Subsequent rainfall events may trigger further knickpoint formation and upslope migration, channel incision and widening, and depositional fan and ridge formation. Between high intensity rainfall events, lower intensity events and gravitational diffusion may gradually smooth the shape of the gully. Eventually, if detachment capacity significantly exceeds transport capacity, the gully may fill with sediment.

Gully erosion rates and evolution can be monitored in the field or modeled on the computer. Field methods include dendrogeomorphology **?** and permanent monitoring stakes for recording erosion rates, extensometers for recording mass wasting events, weirs for recording water and suspended sediment discharge rates, and time series of surveys using total station theodolites **?**, unmanned aerial systems (UAS), airborne lidar, and terrestrial lidar **??**.

With terrestrial lidar, airborne lidar and UAS photogrammetry there is now high enough resolution topographic data to morphometrically analyze and numerically model fine-scale landscape evolution in GIS including processes such as gully formation and the development of microtopography. Gully erosion has been simulated with the Revised Universal Soil Loss Equation Version 2 (RUSLER) in conjunction with the Ephemeral Gully Erosion Estimator (EphGEE) **?**, while gully evolution has been simulation for detachment capacity limited erosion regimes with the Simulation of Water Erosion (SIMWE) model

??. Now numerical landscape evolution models that can simulate steady state and dynamic flow regimes and can dynamically switch between soil erosion regimes are needed to study fine-scale spatial and short-term temporal erosional processes.

The numerical landscape evolution model r.sim.terrain was developed to simulate the spatiotemporal evolution of landforms caused by shallow overland water and sediment flows at spatial scales ranging from square meters to thousands of kilometers and temporal scales ranging from minutes to years. This open source, GIS-based landscape evolution model can simulate either steady state or dynamic flow regimes, dynamically switch between soil erosion regimes, and simulate the evolution of fine-scale morphological features such as ephemeral gullies. It was designed as a research tool for studying how erosional processes scale over time and space, comparing empirical and process-based models, comparing steady state and dynamic flow regimes, and studying the role of dynamic flow regimes in fine-scale morphological change. r.sim.terrain was tested with a regional scale ($650km^2$) case study and a subwatershed scale ($450m^2$) case study. At the subwatershed scale simulations were compared against a time-series of lidar surveys.

2 r.sim.terrain

r.sim.terrain is a process-based, spatially distributed landscape evolution model that simulates topographic changes caused by shallow, overland water flow across a range of spatiotemporal scales and soil erosion regimes using either the Simulated Water Erosion (SIMWE) model, the 3-Dimensional Revised Universal Soil Loss Equation (RUSLE 3D) model, or the Unit Stream Power Erosion Deposition (USPED) model. SIMWE is a physics-based simulation that uses a Monte Carlo path sampling method to solve the water and sediment flow equations for detachment limited, transport limited, and erosion-deposition soil erosion regimes ?. With SIMWE r.sim.terrain uses the modeled flow of sediment – a function of water flow and soil detachment and transport parameters – to estimate the net erosion and deposition rates. RUSLE3D is an empirical equation for sediment flows in detachment capacity limited soil erosion regimes ?. With RUSLE3D r.sim.terrain uses an event-based erosivity factor, the slope, the flow accumulation, and a 3D topographic factor to model sediment flow. USPED is an empirical equation for net erosion and deposition in transport capacity limited soil erosion regimes. With USPED r.sim.terrain uses an event-based erosivity factor, the slope and aspect, the flow accumulation, and a 3D topographic factor to model erosion-deposition as the the divergence of sediment flows. For each of the models topographic change is derived at each time step from the sediment flow or net erosion-deposition rate and gravitational diffusion. r.sim.terrain can simulate steady state or dynamic flow regimes. During simulations with SIMWE r.sim.terrain can switch between detachment limited, transport limited, and erosion-deposition soil erosion regimes.

r.sim.terrain can simulate the evolution of gullies including processes such as knickpoint migration, channel incision, channel widening, and scour pool and depositional riffle formation along the thalweg of the gully. Applications include geomorphological research, erosion control, landscape restoration, and scenario development for landscape planning and management. r.sim.terrain can simulate landscape evolution over a wide range of spatial scales from small watersheds less than ten square kilometers with SIMWE to regional watersheds of thousands of square kilometers with USPED or RULSE3D.

Table 1. GIS-based soil erosion models

Model	Spatial scale	Temporal scale	Representation	Implementation	Reference
GeoWEPP	watershed	continuous	raster	ArcGIS module	**?**
AGWA	watershed	continuous – event	vector	ArcGIS module	**?**
RUSLE3D	regional	continuous	raster	map algebra	**?**
USPED	watershed	continuous	raster	map algebra	**?**
SIMWE	watershed	continuous – event	raster	GRASS modules	**?**

Table 2. Numerical landscape evolution models

Model	Spatial scale	Temporal scale	Representation	Dynamics	Implementation	Reference
SIBERIA	regional	continuous	raster	steady state	Fortran prog.	**?**
CHILD	regional	continuous	mesh	steady state	C++ program	**?**
Landlab	regional	continuous	raster & mesh	steady state	Python library	**?**
r.landscape.evol	regional	continuous	raster	steady state	GRASS module	**?**
r.sim.terrain	watershed – regional	event – continuous	raster	dynamic – steady state	GRASS module	

This model has been implemented as a Python add-on module for the free, open source Geographic Resources Analysis Support System (GRASS) GIS [2]. The source code is available at https://github.com/baharmon/landscape_evolution under the GNU General Public License v2. This highly adaptable geographic information system (GIS)-based implementation was developed as a research tool for studying the interaction of sediment detachment and transport and the scaling erosional processes over time and space. It supports multithreading and parallel processing to efficiently compute simulations using large, high resolution topographic datasets.

2.1 Simulation of water erosion model

SIMWE – the Simulation of Water Erosion model – is a physics-based simulation of shallow overland water and sediment flow that uses a path sampling method to solve the continuity and momentum equations with a 2D diffusive wave approximation **???**. It has been implemented in GRASS GIS as the modules r.sim.water[3] and r.sim.sediment[4].

[2]https://grass.osgeo.org/
[3]https://grass.osgeo.org/grass75/manuals/r.sim.water.html
[4]https://grass.osgeo.org/grass75/manuals/r.sim.sediment.html

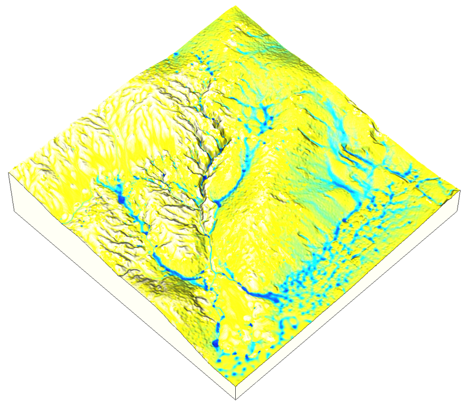

Figure 1. Shallow overland water flow simulated by SIMWE

In SIMWE mode for each time step r.sim.terrain determines the soil erosion regime, simulates water and sediment flows, and then evolves the topography. In an erosion-deposition regime the model computes the partial derivatives of the topography, simulates shallow water flow and erosion-deposition, and then evolves the topography based on the erosion-deposition rate and gravitational diffusion. The same process is used in a transport capacity limited regime except that the topography is evolved based on the transport limited erosion-deposition rate and gravitational diffusion. In a detachment capacity limited regime the model instead computes the partial derivatives of the topography, simulates shallow water flow and sediment flow, and then evolves the topography based on the sediment flow rate and gravitational diffusion. The model simulates dynamic landscape evolution when the time step is less than the travel time for a drop of water or a particle of sediment to cross the landscape. With longer time steps the model simulates steady state dynamics.

2.1.1 Erosion regime

This model can switch erosion regimes at each time step based on the rainfall intensity i_r and the balance of the sediment detachment capacity D_c and the sediment transport capacity T_c represented by the first order reaction term σ which depends on soil and landcover properties. The detachment capacity is the maximum potential detachment rate by overland flow, while the sediment transport capacity is the maximum potential sediment flow rate.

$$\sigma = \frac{D_c}{T_c} \tag{2}$$

where:

σ is a first order reaction term (m^{-1})

D_c is the sediment detachment capacity ($kg\ m^{-1}s^{-1}$)

T_c is the sediment transport capacity ($kg\ m^{-1}s^{-1}$)

When rainfall intensity is very high ($i_r \geq 60mm\ hr^{-1}$) or σ is low ($\sigma \leq 0.01m^{-1}$), then the regime is detachment capacity limited. When rainfall intensity is not very high ($i_r < 60mm\ hr^{-1}$) and σ is high ($\sigma \geq 100m^{-1}$), then the regime is transport capacity limited. When rainfall intensity is not very high ($i_r < 60mm\ hr^{-1}$) and σ is neither high nor low ($0.01m^{-1} < \sigma < 100m^{-1}$), then there is an erosion-deposition regime.

2.1.2 Shallow water flow

The SIMWE model simulates shallow overland water flow controlled by spatially variable topographic, soil, landcover, and rainfall parameters by solving the continuity and momentum equations for steady state water flow with a path sampling method. Shallow water flow $q(x,y,t)$ can be approximated by the bivariate form of the St. Venant equation:

$$\frac{\partial h(x,y,t)}{\partial t} = i_e(x,y,t) - \nabla\ q(x,y,t) \tag{3}$$

where:

(x,y) is the position (m)

t is the time (s)

$h(x,y,t)$ is the depth of overland flow (m)

$i_e(x,y,t)$ is the rainfall excess ($m\ s^{-1}$)

(i.e. rainfall intensity $-$ infiltration $-$ vegetation intercept)

∇ is the divergence of the flow vector field

$q(x,y,t)$ is the water flow per unit width ($m^2\ s^{-1}$).

Diffusive wave effects can be approximated so that water can flow through depressions by integrating a diffusion term $\propto \nabla^2[h^{5/3}(x,y)]$ into the solution of the continuity and momentum equations for steady state water flow. This equation is solved using a Green's function Monte Carlo path sampling method.

$$-\frac{\varepsilon(x,y)}{2}\nabla^2[h^{5/3}(x,y)] + \nabla\ [h(x,y)\ v(x,y)] = i_e(x,y) \tag{4}$$

where:

$\varepsilon(x,y)$ is a spatially variable diffusion coefficient.

2.1.3 Sediment flow

In SIMWE the sediment flow rate $q_s(x,y,t)$ is estimated as a function of water flow and sediment concentration:

$$q_s(x,y,t) = \rho_s(x,y,t)\; q(x,y,t) \tag{5}$$

where:

$q_s(x,y,t)$ is the sediment flow rate per unit width $(kg\; m^{-1}s^{-1})$

$\rho_s(x,y,t)$ is sediment mass density $(kg\; m^{-3})$.

2.1.4 Erosion-deposition

In SIMWE the net erosion-deposition rate is estimated using the bivariate form of sediment continuity equation to model sediment storage and flow based on effective sources and sinks. Net erosion-deposition $d_s(x,y,t)$ – the difference between sources and sinks – is approximated by the steady state sediment flow equation with diffusion:

$$d_s(x,y,t) = \frac{\partial[\rho_s c(x,y,t) h(x,y,t)]}{\partial t} + \nabla\; q_s(x,y,t) \tag{6}$$

where:

$d_s(x,y,t)$ is net erosion-deposition $(kg\; m^{-2}s^{-1})$.

2.1.5 Landscape evolution

The simulated change in elevation $\Delta z(x,y,t)$ due to water erosion and deposition is a function of the change in time, the net erosion-deposition rate, and the sediment mass density **?**:

$$\Delta z(x,y,t) = \Delta t\; d_s(x,y,t)\; \rho_s^{-1} \tag{7}$$

In a detachment limited erosion regime the simulated change in elevation $\Delta z(x,y,t)$ is a function of the change in time, the sediment flow rate, and the mass of water carried sediment per unit area **?**:

$$\Delta z(x,y,t) = \Delta t\; q_s(x,y,t)\; \varrho_s^{-1} \tag{8}$$

where:

ϱ_s is the mass of sediment per unit area $(kg\; m^{-2})$.

Gravitational diffusion is then applied to the evolved topography to simulate the settling of sediment particles. The simulated change in elevation $\Delta z(x,y,t)$ due to gravitational diffusion is a function of the change in time, the sediment mass density, the gravitational diffusion coefficient, and topographic divergence – i.e. the sum of the second order derivatives of elevation **?**:

$$\Delta z(x,y,t) = \Delta t \, \rho_s^{-1} \, \varepsilon_g \, \nabla(x,y,t) \tag{9}$$

where:

ε_g is the gravitational diffusion coefficient $(m^2 s^{-1})$

$\nabla(x,y,t)$ is the topographic divergence (m^{-1}).

3 Conclusions

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Code availability. TEXT

Data availability. TEXT

Code and data availability. TEXT

Sample availability. TEXT

Appendix A

A1

Author contributions. TEXT

Competing interests. TEXT

Disclaimer. TEXT

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