Dynamic Landscape Evolution

Brendan Harmon[a,b,*], Helena Mitasova[a,c], Vaclav Petras[a,c], Anna Petrasova[a,c]

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

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 topographic change based on dynamic flows. 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.

Keywords: landscape evolution, dynamic model, continuity equations

Contents

*Corresponding author
Email addresses: brendan.harmon@gmail.com (Brendan Harmon), hmitaso@ncsu.edu (Helena Mitasova), vpetras@ncsu.edu (Vaclav Petras), akratoc@ncsu.edu (Anna Petrasova)

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 [12]. Numerical landscape evolution models such as the Channel-Hillslope Integrated Landscape Development (CHILD) model [14] and SIBERIA [15] simulate steady state flows over long temporal scales. 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 [6]. A dynamic landscape evolution model is needed to study fine-scale spatial and short-term temporal erosional processes such as gully formation. While most numerical landscape evolution models simulate peak flows at steady state (see Table 2), short-term erosional processes like 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. Theoretically in an erosion-deposition regime depositional ridges should form around the channel. 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.

With sub-meter resolution topographic data from airborne lidar and unmanned aerial systems' (UAS) stereophotogrammetry it is now possible to morphometrically analyze and numerically model fine-scale landscape evolution in GIS including processes such as gully formation and the development of microtopography.

The dynamic landscape evolution model is a process-based, spatially distributed model that solves the water and sediment flow equations with Monte Carlo path sampling method [9] to model mass flows over complex topographies based on topographic, land cover, soil, and rainfall parameters. The modeled flow of sediment – a function of water flow 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. During a simulation the model can switch between dynamic and steady state flow regimes.

The dynamic landscape evolution model has been implemented as the add-on module *r.evolution* [1] for the free, open source Geographic Resources Analysis Support System (GRASS) GIS. This highly adaptable geographic information system (GIS)-based implementation 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. It

[1] `https://github.com/baharmon/landscape_evolution`

supports multithreading and parallel processing to efficiently compute simulations using large, high resolution topographic datasets. It was developed as a tool to study the interaction of sediment detachment and transport and the scaling erosional processes over time and space.

1.1. Theory

1.2. Aims and objectives

- How do erosional processes scale over time and space?
- How do sediment detachment and transport interact?
- Are dynamic flow regimes needed accurately simulate gully formation?

We compared a series of simulations against a times series of lidar surveys to test the hypothesis that dynamic models can more accurately simulate gully formation than steady state models.

1.3. Conceptual model

Table 1: GIS-based soil erosion models

Model	Spatial scale	Temporal scale	Representation	GIS	Reference
RUSLE3D	landscape	annual	raster	map algebra	[7]
USPED	watershed	annual	raster	map algebra	[7]
SIMWE	watershed	annual – event	raster	module	[5]

Adapted from Mitasova et al. [6]

Table 2: Numerical landscape evolution models

Model	Spatial scale	Temporal scale	Representation	Dynamics	GIS	Reference
SIBERIA	landscape	continuous	raster	steady state		[15]
CHILD	landscape	continuous	mesh	steady state		[14]
r.landscape.evol	landscape	continuous	raster	steady state	module	[1]
r.evolution	watershed – landscape	event – continuous	raster	dynamic – steady state	module	

Adapted from Mitasova et al. [6]

2. 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 [5, 8, 9]. It has been implemented in GRASS GIS as the modules r.sim.water[2] and r.sim.sediment [3].

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

2.2. 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.

2.3. Sediment flow

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

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

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

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 ($kg\; m^{-3}$).

2.4. 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 ($kg\; m^{-2} s^{-1}$).

2.5. 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 [6]:

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

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 [6]:

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

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 [13]:

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

where:

ε_g is the gravitational diffusion coefficient ($m^2 s^{-1}$)
$\nabla(x, y, t)$ is the topographic divergence (m^{-1}).

3. Revised universal soil loss equation 3D model

The Revised Universal Soil Loss Equation for Complex Terrain (RUSLE3D) is an empirical equation for computing erosion in a detachment-capacity limited soil erosion regime for watersheds with complex topography [7]. It is based on the Universal Soil Loss Equation (USLE), an empirical equation for estimating the average sheet and rill soil erosion from rainfall and runoff on agricultural fields and rangelands with simple topography [16]. It models erosion dominated regimes without deposition in which sediment transport capacity is uniformly greater than detachment capacity. As an empirical equation the predicted soil loss is spatially and temporally averaged. In USLE soil loss per unit area is determined by an erosivity factor R, a soil erodibility factor K, a slope length factor L, a slope steepness factor S, a cover management factor C, and a prevention measures factor P. These factors are empirical constants derived from an extensive collection of measurements on 22.1m standard plots with an average slope of 0.09°. RUSLE3D was designed to account for more complex, 3D topography with converging and diverging flows. In RUSLE3D the topographic potential for erosion at any given point is represented by a 3D topographic factor LS_{3D}, which is a function of the upslope contributing area and the angle of the slope.

In this spatially and temporally distributed model RUSLE3D is modified by the use of a event-based r-factor derived from the rainfall intensity at each time step. For each time step this model computes the parameters for RUSLE3D – an event-based erosivity factor, the slope of the topography, the flow accumulation, and the 3D topographic factor – and then solves the RUSLE3D equation for sediment flow. The sediment flow is used to simulate landscape evolution in a detachment capacity limited soil erosion regime.

3.1. Event-based r-factor derivation

In USLE and RUSLE the erosivity factor R is the combination of the total energy and peak intensity of a rainfall event, representing the interaction between the detachment of sediment particles and the transport capacity of the flow. It can be calculated as the product of the the kinetic energy of the rainfall event E and its maximum 30-minute intensity I_{30} [2, 11]. In this model, however, the erosivity factor is derived at each time step as a function of kinetic energy, rainfall volume, rainfall intensity, and time. First rain energy is derived from rainfall intensity [2]:

$$e_r = 0.29\; (1. - 0.72\; exp(-0.05\; i_r)) \tag{10}$$

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

Then the event-based erosivity index R_e is calculated as:

$$R_e = e_r\ v_r\ i_r\ t_r \tag{11}$$

R_e is the event-based erosivity index ($MJ\ mm\ ha^{-1}\ hr^{-1}$)
v_r is rainfall volume (mm) derived from $v_r = i_r\ t_r$
t_r is time interval s

3.2. Flow accumulation

The upslope contributing area is determined by flow accumulation. Flow accumulation is calculated using a multiple flow direction algorithm [4] based on A^T least cost paths [3]. The multiple flow direction algorithm implemented in GRASS GIS as the module *r.watershed*[4] is computationally efficient and can navigate nested depressions and other obstacles.

3.3. 3D topographic factor

The 3D topographic factor $LS_{3D}(x, y)$ is calculated as a function of the flow accumulation, representing the upslope contributing area, and the slope. The empirical coefficients m and n for the upslope contributing area and the slope can range from 0.2 to 0.6 and 1.0 to 1.3 respectively with low values representing dominant sheet flow and high values representing dominant rill flow.

$$LS_{3D}(x, y) = (m + 1.0)\ (a(x, y)\ a_0^{-1})^m\ (sin(\beta)/\beta_0)^n \tag{12}$$

where:
LS_{3D} is the dimensionless topographic (length-slope) factor
a is flow accumulation (m)
a_0 is the length of the standard USLE plot (22.1m)
β is the slope angle (°)
m is an empirical coefficient
n is an empirical coefficient
β_0 is the slope of the standard USLE plot (0.09°)

3.4. Sediment flow

The sediment flow is a function of the event-based erosivity factor, the soil erodibility factor, the 3D topographic factor, cover factor, and the prevention measures factor:

$$E = R_e\ K\ LS_{3D}\ C\ P \tag{13}$$

where:
E is soil loss ($kg\ m^{-2}\ min^{-1}$)
R_e is the event-based erosivity factor ($MJ\ mm\ ha^{-1}\ hr^{-1}$)
K is the soil erodibility factor ($ton\ ha\ hr\ ha^{-1}\ MJ^{-1}\ mm^{-1}$)
LS_{3D} is the dimensionless topographic (length-slope) factor
C is the dimensionless land cover factor
P is the dimensionless prevention measures factor

3.5. Landscape evolution

With RUSLE3D the simulated change in elevation $\Delta z(x, y, t)$ is derived from equation 8 for landscape evolution in an detachment limited soil erosion regime and then equation 9 for the settling of sediment particles due to gravitational diffusion.

4. Unit streampower erosion deposition model

The Unit Stream Power Erosion Deposition (USPED) model estimates net erosion-deposition as the divergence of sediment flow in transport capacity limited soil erosion regimes. At transport capacity shallow flows of water are carrying as much sediment possible – more sediment is being detached than can be transported. As a transport capacity limited model USPED predicts erosion where transport capacity increases and deposition where transport capacity decreases. In USPED the influence of topography on erosion and deposition is represented by a topographic sediment transport factor, while the influence of soil and landcover are represented by factors adopted from USLE and RUSLE [7].

With USPED net erosion-deposition is estimated by computing the event-based erosivity factor R_e using Eq. 11, the slope and aspect of the topography, the flow accumulation with a multiple flow direction algorithm, the topographic sediment transport factor, the sediment flow at transport capacity, and the divergence of the sediment flow.

4.1. Topographic sediment transport factor

For USPED the 3D topographic factor (Eq. 12 for RUSLE3D is adapted to represent the topographic sediment transport factor LST – the topographic component of overland flow at sediment transport capacity:

$$LST = U^m\ (\sin\beta)^n \tag{14}$$

where:
LST is the topographic sediment transport factor
U is the flow accumulation (m)
β is the angle of the slope (°)
m is an empirical coefficient

[4] https://grass.osgeo.org/grass72/manuals/r.watershed.html

n is an empirical coefficient.

4.2. Sediment flow at transport capacity

The sediment flow at transport capacity is a function of the event-based rainfall factor, the soil erodibility factor, the topographic component of overland flow, tje landcover factor, and the prevention measures factor:

$$T = R_e \; K \; C \; P \; LST \tag{15}$$

where:
T is sediment flow at transport capacity ($kg \; m^{-1} \; s^{-1}$)
R_e is the event-based rainfall factor ($MJ \; mm \; ha^{-1} \; hr^{-1}$)
K is the soil erodibility factor ($ton \; ha \; hr \; ha^{-1} \; MJ^{-1} \; mm^{-1}$)
C is the dimensionless land cover factor
P is the dimensionless prevention measures factor.

4.3. Erosion-deposition at transport capacity

Net erosion-deposition is estimated as the divergence of sediment flow:

$$d_s(x, y, t) = \frac{\partial(T \; \cos\alpha)}{\partial x} + \frac{\partial(T \; \sin\alpha)}{\partial y} \tag{16}$$

where:
$d_s(x, y, t)$ is net erosion-deposition ($kg \; m^{-2} s^{-1}$)
α is the aspect of the topography (°).

4.4. Landscape evolution

With USPED the simulated change in elevation $\Delta z(x, y, t)$ is derived from equation 7 for landscape evolution and then equation 9 for the settling of sediment particles due to gravitational diffusion.

5. 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/`.

6. Case studies

6.1. Fort Bragg

6.2. Patterson Branch Creek

6.3. Benchmarks

7. Tangible landscape evolution

Tangible Landscape – a tangible user interface tightly integrated with a geographic information system for intuitively sketching in 3D [10]. 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

...

Appendix A.4. Tangible Landscape

...

References

[1] Barton, C. M., Ullah, I., Mitasova, H., 2010. Computational modeling and neolithic socioecological dynamics: a case study from southwest asia. American Antiquity 75 (2), 364–386. URL `http://www.jstor.org/stable/25766199`

[2] Brown, L. C., Foster, G. R., 1987. Storm Erosivity Using Idealized Intensity Distributions. Transactions of the American Society of Agricultural Engineers 30 (2), 0379 –0386.

[3] Ehlschlaeger, C., 1989. Using the A^T Search Algorithm to Develop Hydrologic Models from Digital Elevation Data. In: Proceedings of International Geographic Information Systems (IGIS) Symposium '89. Baltimore, MD, pp. 275–281.

[4] Metz, M., Mitasova, H., Harmon, R. S., 2009. Fast Stream Extraction from Large , Radar- Based Elevation Models with Variable Level of Detail (Figure 2), 237–242.

[5] Mitas, L., Mitasova, H., 1998. Distributed soil erosion simulation for effective erosion prevention. Water Resources Research 34 (3), 505–516.

[6] 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`

[7] Mitasova, H., Hofierka, J., Zlocha, M., Iverson, L. R., 1996. Modelling topographic potential for erosion and deposition using GIS. International Journal of Geographical Information Science 10 (5), 629–641. URL `http://dx.doi.org/10.1080/02693799608902101`

[8] Mitasova, H., Mitas, L., 2001. Multiscale soil erosion simulations for land use management. In: Harmon, R. S., Doe, W. W. (Eds.), Landscape erosion and evolution modeling. Springer, Boston, MA, Ch. 11, pp. 321–347. URL `http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.69.5171{&}rep=rep1{&}type=pdf`

[9] 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.

[10] Petrasova, A., Harmon, B., Petras, V., Mitasova, H., 2015. Tangible Modeling with Open Source GIS. Springer.

[11] Renard, K. G., Foster, G. R., Weesies, G. A., McCool, D. K., Yoder, D. C., 1997. Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). Tech. Rep. 703, US Government Printing Office, Washington, DC. URL `https://www.ars.usda.gov/ARSUserFiles/64080530/rusle/ah_703.pdf`

[12] Temme, A., Schoorl, J., Claessens, L., Veldkamp, A., 2013. 2.13 Quantitative Modeling of Landscape Evolution. Vol. 2. Elsevier Ltd. URL `http://linkinghub.elsevier.com/retrieve/pii/B9780123747396000397`

[13] Thaxton, C. S., 2004. Investigations of grain size dependent sediment transport phenomena on multiple scales. Phd, North Carolina State University. URL `http://www.lib.ncsu.edu/resolver/1840.16/3339`

[14] Tucker, G., Lancaster, S., Gasparini, N., Bras, R., 2001. The Channel-Hillslope Integrated Landscape Development Model (CHILD). Springer US, Boston, MA, pp. 349–388.

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

URL https://doi.org/10.1007/978-1-4615-0575-4{_}12

[15] Willgoose, G., 2005. Mathematical Modeling of Whole Landscape Evolution. Annual Review of Earth and Planetary Sciences 33 (1), 443–459.
URL http://www.annualreviews.org/doi/10.1146/annurev.earth.33.092203.122610

[16] Wischmeier, W. H., Smith, D. D., Science, U. S., Administration, E., Station, P. U. A. E., 1978. Predicting Rainfall Erosion Losses: A Guide to Conservation Planning. Tech. rep., Washington, D.C.
URL https://naldc.nal.usda.gov/download/CAT79706928/