



Short Note

LANDSAP: a coupled surface and subsurface cellular automata model for landform simulation[☆]

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1. Introduction

Recent computer models of landform evolution have focused on surface processes of river networks and hillslopes (e.g., Ahnert, 1976; Kirkby, 1986; Willgoose et al., 1991a, b; Koltermann and Gorelick, 1992; Howard, 1994; Howard et al., 1994; Smith et al., 1997). Most of these models are based on complicated differential equations that are difficult to solve. Chase (1992) developed a cellular automata model (named Gilbert) that uses simple local rules of diffusion, erosion, and deposition to simulate the synoptic effects of fluvial processes. The Gilbert model applies simple rules iteratively to individual cells of a digital topographic grid after storm events (termed *precipitons*) randomly fall onto the grid. The rules are in a sense analogous to the natural processes. For example, precipitons move to lower elevations, simulating water running downhill; the amount of erosion is proportional to the local slope and to the erodibility of the rock, simulating speedier erosion of steeper slope and less erosion of hard rocks (Chase, 1992). The advantage of this approach is that it is simple and yet can still produce realistic first-order geomorphologic features and provide insights into landform evolution processes. The Gilbert model demonstrates that complex landscapes do not require complicated laws (Chase, 1992). Thus the cellular automata approach is ideal for simulating long-term landscape evolution that involves multiple interacting processes.

This short note presents a model (LANDSAP) that extends the Gilbert model to combine both surface and subsurface processes. LANDSAP is designed to simulate the long-term landscape evolution from these processes

and to test the effects of climatic changes. It is not designed to simulate every detail of the processes, but to help us understand the interactions among different processes and the overall effects of such interactions by comparing different simulation scenarios with field observations. A previous version of LANDSAP has been successfully used to model the groundwater sapping processes in Western Desert, Egypt and has provided insights into the paleoclimatic conditions of that area (Luo et al., 1997). The purposes of this Short Note are to describe the programming details in general terms and to make the updated program publicly available. LANDSAP could also be used as a teaching tool to demonstrate system interactions among surface, subsurface, and climatic processes.

2. Description of the model

LANDSAP is written in C programming language and includes the following modules: precipitation, infiltration, diffusion, erosion, groundwater sapping, and climatic change. (The core functions of the program itself and ancillary functions doing pre- and post-processing are listed in Table 1. The codes, along with detailed flow diagram and description of each function, are available via ftp from www.iamg.org site.) Each module hides its internal structure from the outside and this makes upgrade and maintenance easy because each module can be upgraded without having to rewrite the other modules. The programming started from simple modules and evolved to its present form and can continue to evolve as needs arise.

The surface fluvial process in LANDSAP is based on Gilbert model (Chase, 1992). However, LANDSAP improved over the Gilbert model in many ways such as making precipitation magnitude Poisson-distributed and making erosion proportional to flow velocity

[☆]Code available from <http://www.iamg.org/CGEditor/index.htm>.

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Table 1
Functions and brief description

Category	Name	Brief description
Core functions	Main	The main function that controls everything
	Precipitation	Determines the location and amount of precipitation, called by main
	Diffusion	Conducts diffusion (masswasting), called by main and sapping
	Erosion	Conducts erosion and deposition, called by main and sapping
	Sapping	Conducts subsurface groundwater sapping, called by main
	Infiltration	Reads in parameter values and controls call to other functions
	Climax	Conducts climatic change scenario, called by main
	Poisson	Calculates Poisson distribution, called by main
	Lowpt	Finds the lowest point of the 3 × 3 subgrid
	Landread	Reads in initial or result topography file
	Landsave	Saves intermediate modeling results
Ancillary functions	Mkinit	Makes the initial topography file
	Readstart	A standalone function to read and check start file
	Togrid	Converts result topography file to an ASCII file importable by Arc/Info
	Tomgm	Converts result topography file to an ASCII file importable by MGE
	Wread.pro	A PV-WAVE command language program to bring the results into PV-WAVE to make 3-D perspective views
	Calcage	Calculates tufa ages

calculated by the Chezy equation. Groundwater sapping is defined by Laity and Malin (1985, p. 203) as “the process leading to the undermining and collapse of valley head and side walls by weakening or removal of basal support as a result of enhanced weathering and erosion by concentrated fluid flow at a site of seepage.” This process is modeled based on a finite-difference groundwater flow model (Wang and Anderson, 1982), assuming sapping occurs when a critical groundwater discharge value is exceeded (Howard, 1988). LANDSAP extends Howard’s (1988) work by incorporating a transient condition into the groundwater flow calculation.

The surface and subsurface processes interact with each other through infiltration and recharge. Surface water that infiltrates is added to the groundwater as recharge. Groundwater that seeps out becomes surface runoff. This is modeled by initiating a sapping event (*sappaton*) at the location where groundwater seeps out (Luo et al., 1997). The *sappaton* is routed through the system the same way as a precipiton, i.e., by calling the erosion module. The surface water that infiltrates is subtracted from surface runoff and the groundwater that seeps out is subtracted from groundwater by negative recharge, simulating the conservation of the mass of water.

The simulation starts with an initial topography that is a gentle peneplain with a permeable layer (e.g., sandstone or limestone) overlying an impermeable layer (e.g., shale). At each time step, a precipiton (i.e., a storm event, not a single raindrop) is dropped randomly onto

the topographic grid. The precipiton first causes some diffusion (Eq. (1), Table 2) at the cell on which it falls, which simulates weathering and mass-wasting processes such as slope wash, slumping, talus formation, and soil creep (Chase, 1992). The precipiton then moves to the lowest of its 8 surrounding cells, carrying with it some eroded sediment. The amount of erosion is proportional to erodibility of the material, which may change spatially and vertically (rock layers), and proportional to flow velocity of water (Eqs. (2) and (3), Table 2). The precipiton continues running downhill until it has nowhere to go or reaches the edge of the grid. Along its path, the precipiton also infiltrates into the subsurface (Eq. (4), Table 2), recharging groundwater. The amount that infiltrates is subtracted from the surface flow. If the carrying capacity of the precipiton is exceeded at any cell along the path, the precipiton deposits all the sediment it is carrying on that cell. The program also calculates the elevation of the groundwater table, the hydraulic gradient, and the discharge at each cell. If a critical discharge rate is exceeded at any cell, groundwater sapping erosion occurs. The associated slumping is modeled by releasing a precipiton at the cell where sapping occurs, i.e., initiating a *sappaton*. Unlike the precipiton, the *sappaton* will carry some initial sediment, which is equal to the amount eroded by sapping. The amount of sapping erosion is taken to be proportional to the discharge rate over the critical value and to the erodibility of the rock (Eqs. (5)–(7), Table 2). The groundwater that intercepts the surface will run downhill as a surface precipiton and the water table at

Table 2
Equations used in modeling

Process	Equation(s)	Explanation
Diffusion	$P_d = \frac{C_d s e}{w^2} \quad (1)$	<p>P_d = amount of diffusion, expressed in elevation difference [L] s = local slope [dimensionless] e = erodibility [dimensionless] C_d = diffusion proportional constant [L³, to match the dimensions] w = size of each cell [L]</p>
Erosion	$P_e = C_e u e t \quad (2)$	<p>P_e = maximum amount of erosion, expressed in elevation difference [L] u = flow velocity [L T⁻¹] e = erodibility [dimensionless] C_e = erosion proportional constant [dimensionless] t = time step [T]</p>
	$u = \sqrt{\frac{2g}{C_f} ds} \quad (3)$	<p>g = gravitational acceleration constant [L T⁻²] d = depth of water [L] s = slope [dimensionless] C_f = resistance coefficient [dimensionless], usually in range 0.003–0.005</p>
Infiltration	$i = \begin{cases} r & \text{if } r < K, \\ K & \text{if } r \geq K \end{cases} \quad (4)$	<p>i = infiltration rate [L T⁻¹] r = rainfall rate [L T⁻¹] K = saturated hydraulic conductivity [L T⁻¹]</p>
Sapping	$\frac{K}{2} \left(\frac{\partial^2 h^2}{\partial x^2} + \frac{\partial^2 h^2}{\partial y^2} \right) = S \frac{\partial h}{\partial t} - R(x, y, t) \quad (5)$	<p>K = hydraulic conductivity [L T⁻¹] h = hydraulic head or water table [L] S = storage coefficient [dimensionless], which represents the volume of water released from storage per unit area of aquifer per unit decline in head R = recharge [L T⁻¹] x, y = distances in space [L] t = time [T]</p>
	$P_s = C_s (q - q_c) e t \quad (6)$	<p>P_s = amount of sapping erosion [L] q = groundwater discharge rate [L T⁻¹] q_c = critical discharge rate [L T⁻¹] C_s = proportional constant [sapping scale factor, dimensionless] e = erodibility [dimensionless]</p>
	$\mathbf{q} = -K \mathbf{grad} h \quad (7)$	<p>\mathbf{q} = specific discharge [L T⁻¹], vector with components q_x, q_y $\mathbf{grad} h$ = gradient of hydraulic head, a vector with components $\partial h / \partial x, \partial h / \partial y$</p>
Tufa formation	$D_t = C_t q t \quad (8)$	<p>D_t = amount of tufa deposition, expressed in thickness [L] q = groundwater discharge [L T⁻¹] C_t = proportional constant [dimensionless] t = time step [T]</p>

that cell will be lowered by negative recharge for the part becoming overland flow. The program can also simulate the tufa deposited from emerging groundwater. This is modeled in a parametric way by having the rate of tufa deposition proportional to groundwater discharge (Eq. (8), Table 2). The program keeps track of when and where tufa is deposited, which can be used to compare

with real data to constrain paleoclimate conditions (Luo et al., 1997). The model advances to the next time step and the previous procedures are repeated until the end of the simulation.

The different processes, e.g., fluvial, sapping, or climatic change, can be turned on or off by setting the corresponding flag variables stored in a start file. The

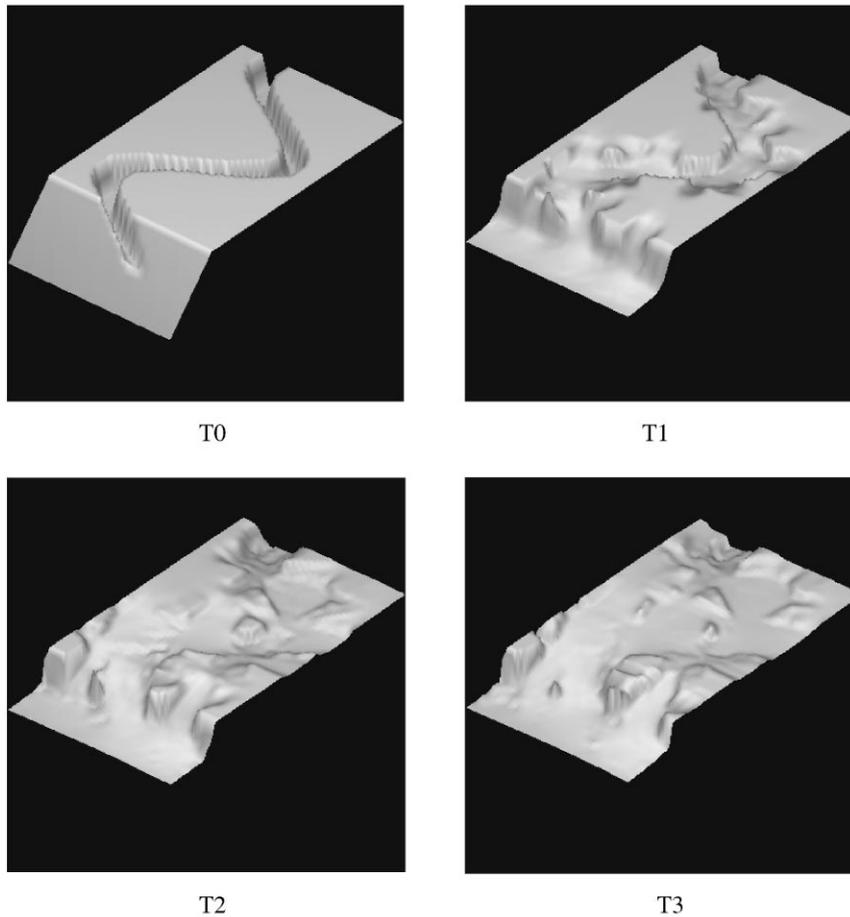


Fig. 1. Example results of applying LANDSAP to model evolution of hypothetical Martian channel that is modified by fluvial and groundwater sapping erosion under climate changing exponentially from wet to dry. Initial topography (at time T_0) has some high hydraulic conductivity zones, simulating fractures. Groundwater sapping generated theater heads where sidewalls intersect fracture zones (at time T_1). As climate became progressively drier, diffusion process dominates, producing degraded and smooth landform (at times T_2 and T_3).

values for various parameters are also stored in that file and can be changed easily. This allows for comparison of different scenarios. The strength of the program lies in its simplicity and its ability to facilitate the understanding of long-term effects of different interacting processes and factors working together as a system, which are sometimes hard to infer directly from observations. However, this program does not attempt to model every detail of every process involved. Some of the limitations and assumptions that have not been discussed previously are listed next:

(a) The initial topography is limited to gentle slopes so that groundwater flow in the permeable layer is primarily in the horizontal direction and the vertical motion can be ignored, i.e., the Dupuit assumption for groundwater flow is valid.

(b) The initial topography has some sub-millimeter-scale roughness to prevent a precipiton from moving downhill along a straight line.
 (c) Tectonic movement is not modeled. However, this could be easily added if necessary.

3. Example and conclusion

Fig. 1 shows how a hypothetical pre-existing Martian channel (at time T_0) evolved as it was modified by coupled surface and subsurface processes under a climate changing exponentially from wet to dry (Arvidson et al., 1997). The climatic change was modeled by changing the amount of precipitation and storm frequency, and thus the amount of erosion and diffusion, over time. The groundwater sapping generated

theater heads along the sidewalls of the channel (at time T_1). These theater heads were developed preferentially along fracture zones, which were assigned higher values of hydraulic conductivity. As the climate continued to become drier, the diffusion process dominated over other processes and formed a degraded and smooth landform (at time T_2 and T_3).

This model is not designed to simulate every detail of the processes involved, but rather to provide insights into the processes, their interactions, and the effect of climatic change over long geologic time scale, which are sometimes difficult to infer directly from observations (Luo et al., 1997). The model could be a valuable tool to explore “what-if” scenarios by turning on or off processes and changing parameter values. This can help us better understand interacting processes, especially where and when we have less “ground truth” control. In addition, the modeling results can be used to create animation so that you can actually see how the landform evolves, particularly valuable for teaching. A Java animation is available on the web at <http://sphere.geog.niu.edu/faculty/luo/mjanim.html>.

This paper presented a computer program LANDSAP that can simulate long-term landform evolution with coupled surface and subsurface processes. The emphasis of this program is placed on simulating the interaction between different processes and the effects of climatic change, not the exact detail of each process. The program can generate realistic first-order geomorphic features and provide insights into paleoclimate conditions through comparison with field observations. It can be used as a tool to study and to teach the interplay between climatic and geomorphic processes.

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