Waterbots

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1. INTRODUCTION

Waterbots are elements of a landscape evolution model based on discrete units of runoff that are able to pick up and deposit sediment. The waterbot model is a cellular automaton model (Toffoli and Margolus, 1989) that captures much of the essence of more detailed hydrologic models. Waterbots are similar to the precipitons introduced by Chase (Chase, 1992) in his discrete model of runoff erosion. In the precipiton model, individual precipitons were viewed as mimicking the effects of single storms. The term waterbot is used here to avoid a suggestion that a discrete waterbot “particle” necessarily represents the result of a particular precipitation event. Instead a waterbot represents an abstract unit of runoff that can reflect the result of either many storms, or of a single storm. Waterbots represent one of potentially several species of geobots, or geologic agents, that might be deployed on a digital landscape to handle a range of geomorphic chores. To illustrate the application of the model, erosion and deposition processes in the Black Mountains, Death Valley, California, are examined, Figure 1.

Waterbot models are not defined explicitly in terms of differential equations, but are instruction-based. The waterbot model is one of a number of quantitative models of sediment transport and landscape change that have been introduced over the past few years (Armstrong, 1976; Ahnert, 1987; Syvitski et al, 1988; Flemings and Jordan, 1989; Willgoose et al, 1991a; Anderson, 1994; Howard 1994; Flemings and Grotzinger, 1996; Tucker and Slingerland, 1997). Most approaches to landscape evolution modeling either solve directly for the effects of water discharge by solving hydrodynamic equations, or use contributing area as a proxy for discharge. Processes that can be modeled using waterbots can usually be approached using one or more of these other methods as well. However, it is often helpful to have several ways of looking at and analyzing a given problem. Waterbot models represent such an alternative, and one that has the advantages of maintaining a close analogy between model structure and the physical system being modeled. Other automata models, distinct from the waterbot model, have been discussed by several authors (Harbaugh and Bonham-Carter, 1970; Chase, 1992; Pratson and Coakley, 1996; Murray and Paola, 1997)

Figure 1. Location map showing northern Black Mountains study area in Death Valley region, California.

A waterbot abstracts the behavior of a discrete volume of water moving downslope under the influence of gravity. The waterbot moves through a system of cells or grid points associated with a digitized landscape. A simple rule or instruction that might govern the motion of a given waterbot is

Move downslope to the neighboring cell with lowest elevation.

In a variation of this rule used here, the waterbot moves to the lowest neighboring cell (out of eight that are available), with some statistical variation added to inhibit the tendency of streams defined on a square matrix to align along the eight compass directions (Fairfield and Leymarie, 1991). A more sophisticated drainage-path generation scheme can be used if desired.
In addition to moving across the landscape, a waterbot must also be able to pick up, carry, and release sediment. Assigned to each cell are one or more numbers representing known or hypothesized cell-specific quantities such as mean elevation of the cell, cell

bedrock geology, thickness of cell regolith, cell infiltration capacity, cell hydrologic roughness, the number of waterbots that have previously, or recently, occupied the cell, and so on. The sediment transport action of the waterbot is a function of one or more of these properties. In most fluvial sediment transport models, local landscape gradient $S$ and local water volume flux $q$ (volume per length transverse to flow direction per time) are two key variables governing the value of sediment flux. Generally, the greater the surface gradient and the greater the flux of water, the greater is the volume flux of sediment that can be carried by the flow. A commonly used parameterization (e.g., Vanoni, 1977; Willgoose et al, 1991a; Paola et al., 1992; Howard, 1994) of the volume sediment flux $q_s$ (volume of sediment that is transported across a unit of length in a unit of time) in terms of $q$ and $S$ is

$$q_s = kq^n S^m$$

where $k$, $n$ and $m$ are constants. In the applications discussed below, a linear transport law is invoked, $n = m = 1$, i.e., sediment flux is taken proportional to water discharge and slope. This choice is made to illustrate the use of the simplest waterbot model in landscape analysis. Specific conclusions for the study problem are therefore valid only within the context of this model assumption. To the extent that sediment transport by running water is nonlinear (e.g., $n \neq 1$ or $m \neq 1$), or that mechanisms other than fluvial transport are important in landscape development, extensions to the model are required. Some of these are discussed below, including implementation of nonlinear transport rules.

In the waterbot model, implementation of Eqn. (1) with $n = m = 1$ implies that the sediment flux carried by a single waterbot is $q_{s,waterbot} = kq_{cell} S$, where $q_{cell}$ is a constant that indexes the flux of water associated with each waterbot. Thus, each waterbot is given an instruction such as

Always carry an amount of sediment that is proportional to local slope.

This algorithm describes erosion and deposition as effected by the waterbot. If the slope increases as the waterbot moves downslope from one cell to another, then it must pick up some sediment in order to be at its “capacity” according to the algorithm. Conversely, the waterbot must drop some of the sediment it is carrying if the slope decreases in going from one cell to a neighboring cell. The dependence on water discharge $q$ is implicit for the case $n = 1$, i.e., the water flux through a given cell is simply proportional to the number of waterbots per unit time that pass through that cell. The description of a nonlinear dependence of sediment discharge $q_s$ on $q$ will be discussed later.

2. THE WATERBOT MODEL

In the simplest version of the model, one waterbot is initially dropped onto each landscape cell of a digital elevation map, Figure 2. The simulations described here are based on USGS digital elevation models (DEMs) (US Geological Survey, 2000) of 1:24000 quadrangles, with cell size 30 m by 30 m, and 1 m vertical resolution. A waterbot is dropped onto a cell that is picked at random, and then followed downslope until it exits the edge of the map. At each step the waterbot may pick up or deposit sediment according to the above rules. Cells continue to be chosen at random, exclusive of previously chosen cells, until every cell on the DEM has received a waterbot. If the linear dimension of the DEM is on the order of $P$ cells, then a typical path followed by a randomly chosen waterbot has a length of order $P$. For a
uniformly populated map (uniform distribution of precipitation), there are \( \sim P^2 \) waterbots. The number of cells traversed by this population of waterbots, and the number of calculations of sediment erosion/deposition, are proportional to \( \sim P^3 \), indicating the rate of increase of computation time with map size. At 30 m resolution, in simulations run on a PC equipped with a 450-MHz processor, erosion-deposition patterns have been studied on areas equivalent to as many as four contiguous 7.5-minute quadrangles (Boring and Haff, 1997). Dropping waterbots onto every cell and following them off the map constitutes one “iteration”. Most of the examples below are based on one such iteration. This is sufficient for illustrating the main features of waterbot dynamics. In general, where landscape evolution is to be followed over a long period of time with significant changes in elevation, multiple iterations would be required (Boring and Haff, 1997).

As the waterbot makes its way downslope, the topography along its path is changed “on the fly”, i.e., the DEM is immediately updated according to whether sediment has been deposited on, or removed from, each cell traversed by the waterbot. In the simulations reported here, when the waterbot leaves the edge of the map, it typically takes some sediment with it, so in the absence of other effects, the mean elevation of the DEM is lowered as each waterbot leaves the calculational domain. The elevation of the edge of the map is held constant through the simulation. Other boundary conditions, such as one accounting for an external (off-map) source of sediment, are easy to implement. Each successive waterbot moves downslope eroding and depositing sediment. This pattern is followed until the last waterbot has exited the map. Infiltration (or exfiltration) during traversal of the map can be described by decreasing (increasing) the quantity of water represented by a single waterbot as it moves along its path, with a corresponding decrease (increase) in sediment transport capacity of the affected waterbot. Effects of changes in infiltration rate, such as those resulting from a transition from bedrock to colluvium (Yair, 1990), can be handled by assigning appropriate permeability data to each DEM cell. Infiltration is taken to be zero here.

During runoff of the waterbot population, the original DEM, designated as \( DEM_0 \), evolves incrementally with the passage of each waterbot, to become a new DEM, \( DEM_1 \), representing the state of the topography after having been iterated through one population of waterbots. If each waterbot iteration is taken to represent the effect of runoff originating on each cell over a period of time \( \tau \), the evolution of \( DEM_0 \) over a time longer than \( \tau \) can be studied by dropping additional populations of waterbots on \( DEM_1 \) to produce \( DEM_2 \), and so forth.

The main focus of the present study is what might be called the response function of the terrain, whereby erosion/deposition patterns are generated, but topographic changes remain small. The response function, \( DEM_1 - DEM_0 \), is the pattern of erosion and deposition resulting from one iteration of the surface. If \( \Delta l \) represents the size of a cell (30 m in the present case), and \( \tilde{R} \) is an effective rainfall intensity associated with sediment-mobilizing rainfall events, then the effective water flux generated from a single cell is \( q_{cell} = \tilde{R}\Delta l \). The volume sediment flux carried by an individual waterbot is \( q_{waterbot} = k\tilde{R}\Delta l S \), in the linear version of Eqn. (1). This flux expression corresponds to a volume of sediment in transport, within a cell, equal to \( k\tilde{R}\Delta l^2 S \). The effective water volume associated with each waterbot is \( \tilde{R}\Delta l^2 \). In the case of multiple iterations, \( \tau \) is the time between iterations. The thickness of sediment carried by a waterbot on slope \( S \), if that sediment were deposited on the surface in a single cell, is \( k\tilde{R}S\tau \), which is independent of \( \Delta l \).

Changes in topography generated by passage of a waterbot as it moves from one cell to an adjacent cell will be less than the preexisting difference in elevation between those cells, \( \Delta z \), if

\[
k\tilde{R}S\tau < \frac{1}{2} \Delta z \tag{2}
\]

This criterion insures that slope is not reversed (which can lead to numerical instability) along a flow path due to passage of a waterbot. Using \( \Delta z = \Delta l S \), Eqn. (2) becomes
Eqn. (3) is essentially the von Neumann criterion for stability of the diffusion equation (Press et al., 1992) in a finite difference approximation with grid size $\Delta l$. This criterion applies to the so-called fully explicit form of the finite difference approximation. The waterbot model is thus mathematically related to an explicit finite difference scheme. The draw back to using an explicit method (or its waterbot analog) is that the von Neumann condition enforces the use of small time steps and hence potentially long computation times. Implicit methods allow longer time steps $\tau$, but at the cost of a loss of small-scale detail. An advantage of the explicit method, besides preserving small-scale detail that may be of interest, is that it allows a direct analogy between the mathematical model and landscape processes. As a consequence of this analogy and the fact that landscape processes are always local, changes in landscape properties can be implemented in waterbot-type models by changes in local rules only. Any subsequent long range effects will take care of themselves. Area-proxy models are non-local, since action at a point depends instantaneously on an extended contributing area. In these models, local changes in surface properties, such as topographic changes due to stream avulsion, can thus affect model structure at a distance. While both modeling formats can compute essentially any landscape process, the local nature of the waterbot rules makes programming relatively straightforward.

3. HILLSLOPE DIFFUSION

Although the focus here is mostly on fluvial transport of sediment as described by the waterbot model, fluvial transport is only one of several processes effecting landscape change. On the upper parts of hillslopes, the effect of running water will be secondary to effects of processes such as rainsplash and creep that depend only on slope. These “diffusive” processes (e.g., Gilbert 1909; Culling, 1965; Kirkby, 1971; Fernandes and Dietrich, 1997; Jyotsna and Haff, 1997; Hanks and Wallace, 1985, et multa alia) can be studied by invoking a transport rule similar to Eqn. (1) but independent of water discharge, e.g.,

$$q_{s,\text{diff}} = DS,$$

where $q_{s,\text{diff}}$ is the volume sediment flux due to diffusion, and $D$ is the hillslope (non-fluvial) diffusivity, here taken to be constant. The landscape agent, analogous to a waterbot, that is responsible for moving diffusing sediment is the diffusionbot. Diffusionbots are distributed across the terrain much like waterbots, with one assigned to each DEM cell. The algorithm that controls the sediment transport properties of a diffusionbot is similar to that for a waterbot, except for two features. Unlike a waterbot, which continues to move until it exits the edge of the map or arrives at a local depression, the diffusionbot carries sediment a (usually) short distance downslope from its initial drop position (perhaps only across a single cell) before it vanishes, leaving behind its sediment load. Because of their slope dependence, fluvial transport and hillslope diffusive transport are both describable by diffusion-like processes at the level of the geobot. The main difference between a waterbot and a diffusionbot, besides the overall sediment transport efficiency factor ($kR/2\Delta l$ or $D$), is that the diffusionbot algorithm carries an extra clause that limits its lifetime to a finite number of cell transitions.

In the barren and nearly vegetation free Black Mountains, California, discussed below, rainsplash (Ellison, 1944; Mosley, 1973) is likely to be an important contributor to hillslope diffusion near ridge tops and on nearly bare hillslopes. However, since infiltration rates are small and soil creep probably slow, overland flow may drive much of the mass wasting on hillslopes. In the simulations below, it is assumed that runoff dominates hillslope processes, and diffusionbots are not deployed.

4. BEDROCK EROSION
The bedrock erosion rate $(\frac{\partial z}{\partial t})_{br}$, where $z$ is elevation, has been modeled (Howard and Kerby, 1983; Howard, 1994) as a function of the applied bed shear stress $\tau$. Because shear stress is an increasing function of water flux and of slope, the erosion rate is set equal to an expression similar to the right hand side of Eqn. (1),

$$\frac{\partial z}{\partial t}_{br} = k_{br} q^{\mu} S$$  \hspace{0.5cm} (5)

where $k_{br}$, $\nu$ and $\mu$ are positive constants. For the purposes of the present study, Eqn. (5) is employed in its linear form, with $\nu = \mu = 1$, in which case $k_{br}$ has dimensions of inverse length. Rewriting Eqn. (1) as $q_{potential,s} = kqS$, where $q_{potential,s}$ is the potential sediment flux that the flow could carry if the bed were alluvial, and combining with Eqn. (5) for $\nu = \mu = 1$, gives

$$\Delta z_{br} = \tau k_{br} q_{potential,s}$$  \hspace{0.5cm} (6)

for the change in elevation $\Delta z_{br}$ of bedrock in time $\tau$. For a single waterbot, the eroded bedrock thickness $\Delta z_{br,waterbot}$ as a sediment thickness equivalent becomes

$$\Delta z_{br,waterbot} = \frac{tk_{br} \Delta S}{\phi}$$  \hspace{0.5cm} (7)

where $\phi$ is the porosity of the eroded bedrock when deposited as sediment. Volume is not conserved under bedrock erosion since $\phi < 1$ (i.e., $\Delta z_{br,waterbot} \neq \Delta z_{br}$). Eqn. (7), rewritten in terms of differentials, relates the time derivative of elevation $\partial z / \partial t$ to its spatial derivative $S = -i z / \partial x$, and thus describes the unidirectional propagation of a topographic wave. When sufficient alluvium is present, the corresponding relation is diffusional, as discussed above, not wavelike, so a mixed bedrock-alluvial channel combines zones of diffusion and wave propagation. One waterbot algorithm that reflects Eqn. (7) and simultaneously handles the presence of bed alluvium, if present, is

(i) If possible, carry an amount of sediment that is proportional to local slope. However, (ii) if not enough bed sediment is available, pick up what is available. If necessary, erode a thickness of bedrock equal to Eqn. (6) and add the corresponding thickness of sediment, Eqn. (7), to the existing load, but don’t erode so much bedrock that capacity is exceeded.

At each cell, each waterbot checks this rule, and then picks up sediment, deposits sediment, or erodes bedrock as necessary. The specified rule produces no bedrock erosion when the alluvial bed thickness is great enough to satisfy flow transport capacity. Other bedrock erosion algorithms could be implemented. For example, one might wish to study the effects of a rule in which bedrock erosion increases with sediment load, up to a point, reflecting the effectiveness of abrasion tools for bedrock erosion.

In the Black Mountains example given below, information on bedrock geology was scanned in from a suitable geologic map (Hunt and Mabey, 1966), then scaled and overlaid on the 1:24,000 Furnace Creek, California, DEM used to derive elevation information. Each DEM cell was assigned a numerical value representing the corresponding mapped geologic unit. The DEM elevation represents bedrock elevation plus regolith or alluvium thickness. In regions of mapped alluvium, alluvium is assumed to be thick, so that over the period of the simulation bedrock is never exposed. In areas of nominal bedrock exposure, as indicated on the geologic map, a thin layer of regolith was specified. The regolith thickness is represented by another overlay on the DEM. The thickness of this layer depended on assumptions made for each simulation. A set of waterbots was dropped onto the landscape, and proceeded to erode and deposit alluvium and regolith, respecting the presence of bedrock as required. In the simulation examples below,
which all run over time scales short compared to the time required for substantial bedrock incision, the effect of bedrock is mostly to limit erosion in the canyons, and to enhance erosion on fans in cases where flows exiting the canyons are under capacity.

5. WEATHERING

Weathering contributes to an increase in the thickness of hillslope regolith with time. The weathering rate depends upon the depth of bedrock below the topographic surface. In the simulation examples shown here, which involve only a single iteration of waterbots, weathering depth is simply postulated. However, more generally, weathering can be simulated by dropping weatherbots onto the landscape. After producing weathering products according to a given set of instructions, the weatherbots vanish. Weatherbots might be instructed to produce a specified incremental increase in regolith thickness where existing regolith thicknesses are less than some threshold thickness. In regions of regolith that exceed this thickness, no new regolith is produced. This algorithm can of course be implemented repetitively on each cell of the DEM without explicitly creating weatherbots. The advantage of using weatherbots comes into play where more spatially complex weathering processes might be indicated. For example, to study the effectiveness of water at promoting weathering, weatherbots can be instructed to move downslope a few cells, producing an given increment of thickness of regolith at each step, before vanishing. This behavior generates weathering rates that depend on convergence of topography.

6. OTHER LANDSCAPE TRANSPORT PROCESSES

Two other transport processes of importance in steep terrain are landslides and debris flows. Landsliding, a diffusion-like process effective on steep slopes, can be modeled using specialized diffusionbots. The explicit treatment of landslides is beyond the scope of the present paper and is not considered further here. (See, however, the caption to Figure 8).

Debris flows (e.g., Hooke, 1967; Whipple and Dunne, 1992; Iverson, 1997) are another important landscape process. The importance of debris flow transport relative to fluvial transport depends on slope, lithology, vegetation, weathering, colluviation rates and environmental factors such as distribution of rainfall. Fan deposits revealed in shallow gullies in the Black Mountains study area show substantial layering, sorting and imbrication of clasts of the kind expected from a braided stream, with intermixing of more poorly sorted, matrix-supported gravels representative of debris flows. The apparent importance of stream flow may be misleading, however, since reworked debris flow material can masquerade as primary braided stream deposits (Blair and MacPherson, 1993). For purposes of illustration, the present study treats all transport as fluvial.

Debrisbots may be defined in a way analogous to waterbots, but with a characteristic slope dependence (e.g., a minimum slope is required for continued displacement of the debrisbot as well as a stronger slope dependence during transport (Seidl and Dietrich, 1992)). The release of a debrisbot also requires characteristic initiation conditions (including requirements on colluvial thickness in upland hollows, on initial slope, and on availability of water). The dependence of debrisbot behavior on colluvial thickness and water availability, which in turn depend on the behavior of weatherbots, diffusionbots and waterbots, illustrates how landscape dynamics can be thought of as reflecting the response of the land surface to a society of interacting geologic agents.

7. NONLINEAR EFFECTS

The waterbot model with $n = 1$ is approximately linear, in that doubling the number of waterbots that flow past a point during one iteration approximately doubles the amount of sediment transported past that point. The word “approximately” is used because even though twice as many waterbots represent twice as much water, changes in topography or bedrock exposure during successive passes of waterbots past a given
point during an iteration can cause the amount of sediment transported to deviate from strict proportionality to the number of waterbots. Highly nonlinear events such as stream capture or avulsion can also occur even when \( n = 1 \).

Various empirical engineering formulae have been used as a basis for a description of sediment transport in landscape evolution modeling. Some of these formulae can be put (approximately) in the common form \( q_s \propto \sigma_0^p \), where \( \sigma_0 \) is the applied bed shear stress and \( p \) is a constant exponent. For the case \( p = 3/2 \), with \( \sigma_0 \propto hS \propto u^2 \), where \( h \) is depth of flow and \( u \) is average flow velocity, this power-law relation is similar to the Meyer-Peter and Muller formula (Meyer-Peter and Muller, 1948; Vanoni, 1977). The sediment flux can be written as \( q_s \propto \sigma_0^{1/2} uS \), i.e., \( q_s \) is proportional to stream power (stress times velocity). This expression can be rewritten as \( q_s \propto u \cdot hS = uh \cdot S \), so that, in terms of water flux \( q \), \( q_s \propto qS \). This form is used by Paola et al (1992) in their simulation studies of basin evolution. For the case \( p = 3 \), the resulting sediment flux expression, \( q_s \propto q^2 S^2 \), is similar to the Einstein-Brown formula (Vanoni, 1977). This is essentially the relation used by Willgoose et al (1991a) in their studies of landscape evolution. Both of these formulae originated from studies of the movement of coarse bed material and apply to bedload transport, but not necessarily to the transport of suspended load. In the illustrative examples discussed below of sediment transport in the arid Black Mountains, rates of chemical weathering and soil development are small, and most transported material is assumed to be of bedload caliber, so that use of a sediment transport algorithm based on a bedload formulae is appropriate. In general then one can expect that bedload transport may be nonlinear and approximately describable by power law relations of the form \( q_s = k q^n S^m \).

For reasons given below, as well as for simplicity, the present discussion of waterbots relies on a linear transport rule \( n = m = 1 \), as suggested by the Meyer-Peter and Muller formula. However, because explicit use of a nonlinear relationship may be required in some applications, a method for incorporating nonlinearity in \( q \) into the waterbot rule is described. (Nonlinear dependence on slope \( S \) requires no special discussion). The nonlinear algorithm is taken to be

\[
q_s = k' q^n S
\]

(10)

with \( n \neq 1 \) and \( k' \) a dimensional constant,

\[
k' = k_n \frac{\Delta l}{q_{\text{cell}}^{n-1}} \left( \frac{\Delta l_0}{\Delta l}\right)^{2n-2}
\]

Here \( k_n \) a dimensionless constant and \( \Delta l_0 \) is an arbitrary but fixed length scale. The reasons for choosing this form for \( k' \) are discussed below. In terms of the number \( N \) of waterbots arriving at a given cell, \( q = Nq_{\text{cell}} \). To implement the nonlinear algorithm, \( N \) is computed during an initial conditioning iteration, and then stored (and updated each subsequent iteration) in a database associated with each cell, along with any other cell-specific information of interest. The number \( N \) can then be observed by any arriving waterbot, and used to modify its sediment transport rule.

Communication between otherwise independent waterbots by means of marking a path to indicate that it has been previously traveled is the same strategy used by social insects such as ants to generate cooperative (nonlinear) behavior. A chemical pheromone trail laid down by an initial passage of ants is “read” by other ants who arrive later and adjust their behavior accordingly (for example by following the path). The concept of so-called swarm intelligence has been developed mathematically as a means of coordinating the behavior of otherwise independent agents (Bonabeau, 1999). Here, the waterbots are like the ants. The strength of the numerical pheromone is \( N \), and waterbots adjust their sediment carrying capacity, rather than their path, as a function of \( N \). If it is assumed that all transport is capacity limited, the waterbots move downslope, eroding and depositing sediment as in the linear case, but now according to the modified algorithm,
With the above choice of $k'$, this expression for $q_{s,\text{waterbot}}$ reduces to the linear case when $n = 1$. The thickness of sediment carried by a waterbot and the total amount of sediment removed from a drainage basin in time $\tau$ are both independent of cell size $\Delta l$. In accordance with Eqn. (11), waterbots obey the rule

\[ q_{s,\text{waterbot}} = \frac{1}{N} k' q^n S = k' N^{n-1} q^n_{\text{cell}} S \]

Carry an amount of sediment that is proportional to the local slope and to $k' q^n_{\text{cell}}$.

Upon entering a new cell, the waterbot’s sediment-carrying capacity can then change either because slope changes, as in the linear case, or because the number of associated waterbots changes (the nonlinear effect).

Sediment transport in stream channels is normally considered to be concentrative, i.e., nonlinear in discharge. The original Meyer-Peter and Muller formula (Meyer-Peter and Muller, 1948; Vanoni, 1977) is nonlinear because of the presence of an entrainment threshold. In the approximation $q_s \approx a_{0}^{3/2}$, the threshold is neglected. Use of the power-law approximation to the Meyer-Peter and Muller formula is equivalent to assuming that most sediment transport occurs in large discharge events. The power-law approximation to the Einstein-Brown formula, in contrast, is explicitly nonlinear ($n = 2$).

Engineering sediment transport formulae such as Meyer-Peter and Muller and Einstein-Brown are generally instantaneous (or short-time-averaged) formulae derived from flume experiments that relate sediment flux to instantaneous water flux. However, the sediment transport relation Eqn. (1) is an effective relation in which individual stream widths are not resolved (stream widths in the study area are usually less than the 30 m resolution of the DEM) and which may represent an average over many storms. The tendency for stream width to increase in the downstream direction according to the rules of hydraulic geometry (Leopold et al, 1995) tends to moderate nonlinearities in $q$ when stream width is unresolved, since $q$ does not increase as fast as total discharge $Q$. Moreover, when $q$ is interpreted as a time average, its physical meaning as a transport variable, and the resulting exponent $n$ in Eqn. (1), depend upon the spatial distribution of precipitation. In climates where the precipitation responsible for sediment transport tend to be localized, as in the Death Valley example studied below, discharges in major stream channels may be composed primarily of occasional pulses of water and sediment that reflect the incidence of storms whose footprint is less than the area of the drainage basin. The sediment transport effects of such storms are additive (linear) in the sense that two pulses of water of equal size separated in time carry (approximately) twice the sediment of a single pulse, independent of the degree of nonlinearity in sediment transport obtaining within the pulse itself. If a drainage basin is subjected to many localized precipitation events, each of areal extent substantially less than the area of the basin, the effective sediment transport algorithm corresponds to the linear version of Eqn. (1). The effects of the pulses are separated in (real) time and simply add up linearly. The effective sediment transport algorithm in such a case would be linear even if the actual (instantaneous) sediment transport were highly nonlinear. On a scale smaller than the precipitation footprint, the nonlinearity reemerges. The runoff events associated with these sub-basin footprints are similar to the precipitons introduced by Chase (Chase, 1992).

For these reasons, in the illustrative examples of the waterbot model given below, it is assumed that the effective sediment transport algorithm, Eqn. (1), is linear.

8. OTHER TOPICS: CONTRIBUTING AREA AND HYDROGRAPHS

In the waterbot model, water discharge is a function of the physical precipitation area, which may be different from the topographic contributing area. The contributing area is the footprint of the “cloud” that drops the precipitation. In most of the examples give below, the precipitation extends over the entire map so that contributing area is proportional to drainage basin area. The motion of the waterbots automatically accounts for contributing areas that may be different from the geometrical contributing area.
Sometimes an estimate of the hydrograph may be desired as well. This requires that the time evolution of the waterbot population be followed. As a first cut at generating an approximate hydrograph under given conditions of precipitation, each waterbot is supplied with a list on which is written not only the amount of sediment that it is carrying at any instant, but also the current number of cells it has traversed to reach its present location. A large number of cells recorded on the list when the waterbot is at a particular point on the map means that the waterbot has come from far away, and therefore is likely to have arrived there later than other waterbots with smaller numbers on their internal data lists. Figure 3 shows the “pseudo-hydrograph” for a point near the mouth of Gower Gulch (a locality discussed further below). The gentle rising limb and abrupt falling limb of the pseudo-hydrograph (a pattern opposite that commonly seen in nature) reflect the fact that it is travel distances rather than arrival times that are binned. The pseudo-hydrograph is a only rough proxy for the hydrograph. To arrive at a better approximation, waterbots can “compute” elapsed time, rather than accumulated distance, by summing incremental travel times at each step of the waterbot journey. Travel time increments across each cell can be estimated on the basis of cell properties such as local slope, pheromone number and surface roughness. Generation of a hydrograph does not require coordination between the initial release and subsequent motion of waterbots, which, as before, move asynchronously over the landscape.

Figure 3. Distribution of travel distances in units of cells traversed, for waterbots arriving at the mouth of Gower Gulch. A better approximation to the unit pseudo-hydrograph can be generated by requiring each waterbot to integrate its time of passage from source cell to canyon mouth, and plotting counts versus arrival times rather than distance. This modification has not yet been exercised in the author. The two humps in the plot represent populations of waterbots arriving from the main Gower Gulch drainage (first hump) and the more distant Furnace Creek drainage (second hump).

9. EXAMPLE – SETTING UP THE DEM AND RAINING ON THE BLACK MOUNTAINS

In this section the waterbot model is applied to erosion and deposition on a specific example of natural terrain. The purpose of this and the following sections is to suggest how waterbot-type models can be used to help pose questions, suggest answers and test hypotheses about landscape processes. Figure 4 shows an aerial photograph of a section of the northern Black Mountains, Death Valley, California, that includes some key features of the study area, as annotated on the photo. This image corresponds to part of the Furnace Creek, California, 1:24,000 quadrangle. The study area is represented in the DEM by about 5.7 \times 10^4 cells, or approximately 50 km\(^2\) at 30 m resolution. The faulted range front of the tectonically active Black Mountains is bordered by alluvial fans in Death Valley on the west. On the east and north, this part of the mountain range is bordered by Furnace Creek, which historically flowed around the extreme north end of the range to reach the Death Valley sink. In the study area there are two main bedrock units, sandstones and conglomerates of the late Miocene Furnace Creek formation to the north, and volcanic rocks of the middle to late Miocene Artist Drive formation to the south (Wright et al, 1999). Maximum elevation in the study area is about 550 m, but more typical elevations are around 120 m. The base of the mountains in Death Valley is near sea level, so elevation and relief are similar. A hyper-arid climate (~0.04 m precipitation per year (Hunt and Mabey, 1966)) supports only a sparse vegetation, and soils are thin to absent over much of the study area.

Using DEMs as input for landscape simulation creates well-known problems such as pit-artifacts and unnatural stream alignments. A brief discussion of some of these problems is given below to help illustrate the use of the waterbot model, but is not meant to be a complete treatment of problems arising from use of DEM data.

Figure 4. Vertical aerial photograph of northern Black Mountains study area.

In preparing the DEM elevation map for use in the simulation, numerical artifacts in the form of closed areas or pits must be filled. If unremoved, these pits intercept waterbots and prevent their escape to the edge of the map. Accordingly, we first condition the DEM by running a population of conditioning bots that find pits and fill them. Conditioning bots are similar to waterbots in that they move downslope, but
when they find themselves trapped in a closed pit, they deposit sediment and then vanish. The material to fill the pit is carried with the conditioning bot from its inception, and does not come from some other point on the landscape. Because filling a pit can cause a blockage that creates a pit on a neighboring cell, conditioning bots are run iteratively, i.e., in several populations, until small pits are removed. Larger “pits” may be real closed depressions, whose effect on landscape evolution one may want to study. The conditioning process produces only minimal filling of these features.

Figure 5a. Drainage patterns in northern Black Mountains showing all cells with greater than a 1000-cell contributing area. Stream courses on low-slope playa surface to west are to be disregarded.

Figure 5b. Same as (a) but showing all cells with greater than a 100-cell contributing area.

A second problem with routing waterbots over the surface stems from the square DEM grid. Each grid point has 8 nearest neighbors (N, NE, E, SE, etc). As implemented here, waterbot motion is restricted to these eight directions. Because, especially on smooth surfaces, small changes in orientation of the surface can cause large changes in the direction of the lowest neighboring cell, unnatural drainage patterns can result. The lore on constructing digital drainage patterns that are reasonably faithful to the natural patterns is large and beyond the scope of this contribution. We have used a stochastic method for routing waterbots that provides a set of weights for the probability of reaching a neighboring downslope cell. This method produces enough variation to moderate (but not eliminate) some of the artificialities (e.g., occurrence of many parallel, straight stream channels) sometimes seen on DEM-derived drainage nets. When the computed drainage net is compared with the paper topographic map, major stream channels tend to be in the right place.

Figure 5c. Same as (a) but showing all cells with greater than a 2-cell contributing area. The linear white features are ridge tops.

Another potential problem, seen on low-slope terrain, such as the alluvial fan surfaces northeast of Furnace Creek, Figure 4, is that the raw DEM data, produced by rounding to the nearest meter, creates unnatural stair-step topography. This artifact does not significantly influence the results presented here, but would need to be addressed for studies focused on low-slope terrain. Once the map has been conditioned, waterbots can be used to investigate landscape processes. Drainage patterns and discharge magnitude are determined by choosing $k = 0$ in Eqn. (1), and allowing a population of waterbots to run off the map. The waterbot trajectories mark drainage paths. Because $k = 0$, no erosion occurs. A number can be associated with each cell of the DEM that records a running sum of the number of waterbots that have passed that cell. Figure 5 shows computed drainage paths, computed in this way, made up of cells with more than 2, 100 and 1000 waterbot counts, respectively. The paths are color coded, showing the change in water flux as one moves downslope. Decreases in water flux downslope in some locations are due to lateral dispersal of waterbots, usually caused by local alluviation of the channel. For nearly horizontal surfaces, such as on the playa in the extreme western part of the study area, Figure 4, surface slopes derived from DEM data are inaccurate, and details of waterbot trajectories are not meaningful there. This causes no problems for the present study, which focuses on steeper and more rugged terrain regions of the DEM. In Figure 5, a white background indicates runoff is less than the specified minimum. In Figure 5c, where the lower waterbot count is 2, the white linear features correspond to the ridge tops, on which the waterbot count equals unity. Diffusive processes would be dominant there.

To illustrate the response of this landscape to precipitation runoff, under the conditions assumed above, the hillslopes in Figure 4 are taken, for the moment, to be transport limited – that is, enough detached sediment is assumed to be available in each cell to saturate the sediment-carrying capacity of each waterbot. The thin soils imply quick appearance of Horton overland flow, and hillslope processes are thus assumed to be driven solely by overland flow. Figure 6 shows the response function $DEM_1 - DEM_0$ of the
model terrain, and indicates net erosion on hillslopes, net deposition in low-slope canyon reaches, and net deposition on the proximal part of the fan for the case of an initial 1 m thickness of regolith or alluvium on hillslopes and in channels. Further iterations would each reproduce similar patterns until elevations had increased or decreased sufficiently to begin to make significant changes in waterbot trajectories and the value of local slope. Groups of cells specified by the response function as depositional define regions where sediment should tend to accumulate on the existing topographic surface under the model assumptions (which include capacity-limited transport and lack of landsliding or diffusion). Lower-slope areas of canyons tend to be zones of continuing sediment accumulation (white), according to the computed response function. Local, temporary accumulations of sediment are expected to occur due to fluctuations in intensity and distribution of rainfall, as evidenced by minor damming of side-channels by Gower Gulch alluvium. But in general, the northern Black Mountains canyon system is sediment poor, with canyon bottoms floored either by bedrock or a thin alluvial cover. The computed response function is at odds with observation, indicating that one or more of the assumptions of the model are probably incorrect.

Canyons will remain relatively free of sediment of course if little sediment is produced on hillslopes in the first place, contrary to the assumption of 1 m of regolith in the previous simulation. To examine this scenario, the location of bedrock must be specified. Bedrock geology is overlayed on the DEM using the geologic map of Hunt and Mabey (1966), Figure 7. On the basis of the geologic map, each cell is assigned a variable that indicates the instantaneous thickness of transportable material overlying the bedrock. In areas mapped as alluvium (yellow) in Figure 7, the sediment cover is set to an arbitrary but large value. Where bedrock geology is mapped, a thin or vanishing covering of regolith or alluvium is assumed and assigned to each cell. In the simulation presented here, bedrock itself is not eroded. Figure 8 shows the landscape response function in the extreme case of bare bedrock hillslopes and bedrock canyon bottoms. In this scenario, there is no erosion or deposition on the bedrock portion of the map. Waterbots exiting the bedrock canyons, however, are starved for sediment, causing proximal incision (black) of alluvial fans. Eroded material is deposited near the toe of the fan.

Observation shows, however, that modern fan surfaces in the study region, with an exception discussed below, are not significantly incised. The simulation model must then satisfy two requirements that work in opposite directions: there must be enough sediment in the canyons that the waterbots moving down the channel are not starved for sediment, thereby causing incision of the fan. At the same time the hillslope sediment supply must be meager enough that the canyons are kept relatively free of alluvium. As an aid to conceptualization of these points, sediment mobilization, transport and deposition are summarized below in terms of a set of dimensionless transport numbers.

The dark-colored patch south of Gower Gulch in Figure 8 is a zone of simulated landsliding material. The depositional lobe on the facing fan suggests an origin for the darkly varnished, ancient, incised fan remnant seen in Figure 4. This feature is not discussed further, except to note that if a landslide dams a channel, the waterbot model responds to appearance of the local depression by dropping its sediment load. Thus a dammed channel self-alluviates until, in the absence of other effects, the dam is overtopped, followed by incision of the damming deposit. In the present example a glob of sediment is then deposited on the fan, as shown (white) in Figure 8. This example also illustrates that the existence of a connected

Figure 6. Erosion-deposition map of study area with von Neumann number $kR\tau = 0.033$, i.e., transport thicknesses are small. Here regolith thickness was set at 1 m. Flows emerging from canyons tend to produce fan deposition (white). Zones of deposition occur in Gower Gulch and other canyons in low-slope reaches.

Figure 7. Geology of study area (Hunt and Mabey, 1966), showing the Furnace Creek Formation and the Artist Drive Formation. Except for a short reach near its mouth, Gower Gulch incises the Furnace Creek Formation.

The dark-colored patch south of Gower Gulch in Figure 8 is a zone of simulated landsliding material. The depositional lobe on the facing fan suggests an origin for the darkly varnished, ancient, incised fan remnant seen in Figure 4. This feature is not discussed further, except to note that if a landslide dams a channel, the waterbot model responds to appearance of the local depression by dropping its sediment load. Thus a dammed channel self-alluviates until, in the absence of other effects, the dam is overtopped, followed by incision of the damming deposit. In the present example a glob of sediment is then deposited on the fan, as shown (white) in Figure 8. This example also illustrates that the existence of a connected
drainage network is not required to implement waterbot simulations, nor is a priori knowledge of the existence of local depressions.

**Figure 8** Same as Figure 6, but for extreme case of no regolith or alluvium on mountain slopes or in canyons. Waterbots are under capacity when they reach the fan surface, and tend to incise the fans (black). The dark square south of Gower Gulch represents a region in which a simulated landslide was created. In the figure, landslide debris has been mobilized by stream flow and deposited on the fan (white). Such a deposit may correspond to the anomalous incised ancient fan remnant seen in the aerial photograph, Figure 4. Space considerations prohibit further discussion of this interesting feature.

10. DIMENSIONLESS NUMBERS IN THE BLACK MOUNTAINS

The behavior of each waterbot is a function of a small number of variables and algorithms, but a typical simulation involves the motion of thousands or millions of waterbots. As an aid to interpretation and understanding the resulting calculations, key aspects of the simulation (and of the physical system) can be often be “compressed” into a “few cell” semi-quantitative model. This observation is summarized in the following conjecture:

If there is a simple verbal explanation for the origin of a geologic landform or the behavior of a geomorphic process, then there must be a simple quantitative model depending on only a handful of variables and rules that will replicate the essentials of that behavior to the level of the verbal description.

Otherwise, what would be the meaning of such an explanation? For the problems studies here, a three-cell model is sufficient. Such a model can be represented by a set of three dimensionless numbers whose values reflect the response of the three main landscape units of the problem – hillslopes, canyons and fans – to waterbot sediment transport. Such dimensionless numbers (e.g., Willgoose et al, 1991b) are part of the interpretive toolbox that ought to accompany any many-degrees-of-freedom model like a cellular automaton model or a set of differential equations.

**Figure 9.** Long profile of Gower channel, and slope of same channel. Gradient shown on left axis. Although generally concave-up shape, the channel has significant zones of upward convexity in the headlands and in the vicinity of the range front. The range-front convexity is the result of the inability of stream erosion to keep up with mountain uplift. Although Gower Gulch lies mostly in the erodible Furnace Creek Formation, the extreme lower reach of Gower Gulch crosses the more resistant Artist Drive Formation, probably due to stream antecedence, thereby increasing the local stream convexity. Portions of the middle reaches of Gower Gulch have very low slopes – lower than the slope of the alluvial fan. These reaches, which tend to be zones of accumulation of alluvium, can be seen in the erosion-deposition map in Figure 6. Similar low-slope reaches exist in other canyons in the study area. A notable feature of these reaches, especially in Gower Gulch, is their periodicity. Periodic slope changes in DEM’s are suspect because of artifacts arising during construction of the maps. Thus, on very low-slope terrain, rounding of elevations to the nearest whole meter produces false stair-step topography, some hints of which can be seen on low alluvial slopes in the northwest portion of Figure 5c and 6. Whether the stair steps in Gower Gulch are real or not, these middle reaches do have low mean slopes that are effective at trapping sediment.

Three appropriate dimensionless “transport” numbers are the hillslope transport number, \( E_h \), the channel transport number, \( E_c \), and the fan transport number, \( E_f \). The hillslope number \( E_h \) is defined for the present set of simulations as the ratio between (i) the existing average thickness of regolith \( h_r \) covering the hillslopes, and (ii) the hillslope transport capacity thickness \( kR \tau S_h \), i.e., the average thickness of material that can be carried by a waterbot on slope \( S_h \). Here \( S_h \) is average hillslope gradient. Thus

\[
E_h = \frac{h_r}{kR \tau S_h} \tag{12}
\]
"E_h" is also the ratio of the rate of production of hillslope regolith to the rate at which waterbots can remove that regolith. If \( E_h > 1 \), then regolith accumulates on hillslopes by weathering and detachment processes, while \( E_h < 1 \) implies that slope processes represented by the waterbots can (potentially) remove transportable sediment faster than it is produced. Under conditions of dynamic equilibrium (Hack, 1960), where for example uplift rates equal erosion rates everywhere, \( E_h = 1 \).

**Figure 10.** Original stream pattern in Gower Gulch. Furnace Creek has been restored to its original course down Furnace Creek Wash. Coloration of streams indicates approximate amount of discharge. Width of streams is enhanced for greater visibility.

**Figure 11.** Stream pattern after diversion of Furnaces Creek into Gower Gulch in 1941. Coloration of streams indicates approximate amount of discharge. Width of streams is enhanced for greater visibility.

For the reasons discussed above, it is assumed that hillslope transport is driven mostly by overland flow. However, if hillslope processes were instead dominated by diffusion rather than runoff, then the denominator in Eqn. (12) would be defined in terms of diffusionbot parameters (see Eqn. (4)) rather than waterbot parameters. Other variables would define \( E_h \) where landslides dominate hillslopes. Sticking to waterbots, \( E_h \) would be expected, over the long run, to be less than or equal to unity, since regolith does not grow in thickness indefinitely. However, over shorter periods of time, \( E_h \) may be greater than unity, depending on fluctuations in weathering and transport rates.

\[
E_c = \frac{\text{Min}(h_r, kR \tau S_h)}{kR \tau S_c} \quad (13)
\]

If \( E_c > 1 \), then, on average, a waterbot on the hillslope carries a greater thickness of sediment than it can carry in the channel. Channel aggradation occurs when \( E_c > 1 \). Conversely, if \( E_c < 1 \), the transport
capacity of the channel waterbot exceeds the thickness of sediment it carries when on the hillslope, so that it may pickup transportable sediment from the channel bed and the channel is eroded. In dynamic equilibrium, $E_c = 1$.

Finally, the fan transport number $E_f$ is the ratio of (i) the thickness of sediment carried by a waterbot in the channel, $\min(h_r + h_a, k\tau S_f)$, to (ii) the maximum thickness it can carry on the fan $k\tau S_f$, where $S_f$ is average fan slope and $h_a$ is the average thickness of alluvium in the channels. Thus

$$E_f = \frac{\min(h_r + h_a, k\tau S_f)}{k\tau S_f} \quad (14)$$

$E_f > 1$ implies fan aggradation and $E_f < 1$ implies fan incision. Again, in dynamic equilibrium, $E_f = 1$.

The first simulation model discussed above for the northern Black Mountains, Figure 6, where hillslopes and canyons were assumed to be capacity limited, corresponds to $E_h > 1$, $E_c > 1$ and $E_f > 1$, i.e., regolith is not stripped from the hillslopes, deposition occurs in channels and on fans, and all geomorphic surfaces are transport limited. The second simulation example, where no regolith is present on the hillslopes (or alluvium in the channels), Figure 8, corresponds to $E_h < 1$, $E_c < 1$ and $E_f < 1$, so that incision of alluvial fans can be expected to occur. Neither of these situations corresponds to sedimentation conditions in the study area.

In general, the transport numbers for hillslopes, canyons and fans in the northern Black Mountains appear to reflect a state in which $E_h \leq 1$ (waterbots are able to remove all regolith that develops over time $\tau$), $E_c \leq 1$ (once reaching the channel, waterbots are able to continue transporting hillslope sediment), and $E_f \geq 1$ (there is no incision of proximal part of fan). Further interpretation of the landscape in terms of transport numbers depends upon assumptions about the sediment transport algorithm, and on particulars of topography. For the linear model of sediment transport, the condition $S_h > S_c$ implies hillsides must be weathering limited, $E_h < 1$, otherwise accumulation of debris would occur in the canyons. Similarly, $S_c > S_f$, otherwise fan incision would occur. If neither erosion nor deposition is dominant on the proximal fan, then $h_r = k\tau S_f$ (for $h_a = 0$), i.e., the fan slope is adjusted to the regolith production rate $h_r / \tau$, and the hillside and canyon channel slopes are slopes mostly of transportation.

The above remarks need to be modified if slopes do not follow the relation $S_h > S_c > S_f$ or if sediment is transported according to a different rule than the linear version of Eqn. (1) or if other surface processes are important. A look at waterbot trajectory profiles from ridgeline to toe of fan shows that long-profiles in the northern Black Mountains are not always concave-up, Figure 9. In particular, there are many canyon reaches where local slope is less than, or about equal to, fan slope, Figure 9, and where channel profiles are convex up. In low-slope reaches, local alluviation might be expected to occur until channel slopes have steepened sufficiently to end deposition and allow continued transport of hillslope sediment. However, these lower-than-fan-slope channel reaches tend to have only thin alluvial covers that have not significantly increased channel grade. Deposition in canyon reaches can be avoided by decreasing the thickness $h_r$ of regolith produced in time $\tau$, but then the existing fans would tend to become incised because waterbots are not at their transport capacity when they move onto the fan. For the linear waterbot model as described, it is difficult to produce a sediment erosion and deposition pattern across the study area that reflects observed trends of sediment accumulation. In the model, either too much sediment accumulates locally in canyons or fans become too deeply incised.
If the sediment transport rule is taken to be nonlinear in \( q \) \((n > 1)\), then transport efficiency in the confined canyons will increase relative to hillslopes, and canyon deposition can be avoided, for the same supply rate of loose material from the hillsides. However, erosion rates at the fan head tend to increase substantially, because \( q \) is large there. While sufficiently complicated transport laws can always be advanced that would reflect the desired distribution of erosion and deposition, another possibility is that the observed state of sedimentation is the result of ongoing sediment accumulation in canyons alternating with rapid channel flushing caused by locally severe storms or short-term fluctuations in climate. In this scenario, channel flushing, which can be generated in the model by increasing the effective “rainfall” rate \( \dot{R} \), corresponds to the conditions \( E_h < 1 \), \( E_c < 1 \) and \( E_f < 1 \), i.e., bare hillsides, sediment-free channels, and incised fans. Short periods of flushing and incision followed by periods of lower \( \dot{R} \) and localized sediment accumulation in canyons could correspond to the situation observed today in the study area. Fan incision caused by flushing will tend to fade as a major fan surface feature, because the incised fan channel, being of lower slope \( S_{f, \text{incised}} \) than the older fan surface \( S_f \), may be filled \((E_{f, \text{incised}} > 1)\) during a subsequent period of less intense precipitation. Infilling can be rapid if the volume of the incised channel is small compared to the volume of regolith transported off of the upland hillsides in time \( \tau_{\text{flush}} \), the time between major flushing events. Thus, if the area of the upland drainage contributing sediment to the fan head is \( A \), and if in time \( \tau_{\text{flush}} \) a thickness \( h_{\text{flush}} \) of regolith is removed from \( A \), then the volume of sediment transported to the fan during this time is \( A h_{\text{flush}} \). The volume of a channel of width \( w \), depth \( d \) and length on the order of \( \sqrt{a} \), where \( a \) is fan area, is approximately \( wd \sqrt{a} \). The ratio of channel volume to volume supplied to the fan is \( wd \sqrt{a} / A h_{\text{flush}} \). If \( w = 20 m \), \( d = 3m \), \( a = 1 km \), \( h_{\text{flush}} = 0.01 m \) and \( A = 4 \ km^2 \), corresponding to likely conditions on the small fans in the study area, then the value of this ratio is about 0.05, so 95% of the time, including, evidently, at present, no major incision would be visible. If \( \tau_{\text{flush}} \) (and thus \( h_{\text{flush}} \)) becomes too small, then the volume ratio can exceed unity. This corresponds to a scenario in which sediment moving storms are so frequent that the channel incision never “heals”. In practice the fan would regrade to a new and lower mean slope value.

11. THE CASE OF GOWER GULCH: A CHANGE IN FLOW REGIME

Gower Gulch, Figure 4, is a small canyon that historically received runoff from a drainage basin measuring about 5.9 km\(^2\) in area. In 1941, as part of an engineering project to help protect the Furnace Creek Inn from flooding, flow from the much larger Furnace Creek drainage (of which about 275 km\(^2\) is included on the Furnace Creek DEM) was artificially diverted into Gower Gulch (Troxel, 1974). The response of the Gower drainage system to the greatly increased water and sediment discharge represents a large scale experiment in sediment dynamics on a natural landscape. Response of the Gower Gulch system was studied in the waterbot model by comparing sediment transport in Gower Gulch with and without diversion of Furnace Creek flow. To restore the original flow pattern, Figure 10, a simulated dam was erected across the man-made diversion point and the main Furnace Creek channel was locally deepened on the DEM (compare with the present drainage pattern, Figure 11). Figure 12a and Figure 12b, show details, respectively, of the diversion point before and after dam construction, illustrating the digital engineering of the landscape. Erosion and deposition shown in Figure 6 are computed prior to the diversion of the Furnace Creek flow.

Historically, the diversion of Furnace Creek caused significant incision of the Gower Gulch fan, Figure 4. The incised portion of the Gower fan is strewn with characteristic gray carbonate clasts derived from the Furnace Creek drainage, easily distinguishable from the tan colored debris eroded locally from the Furnace Creek formation in Gower Gulch. Figure 13 shows a close-up view of the incision. Figure 14 shows the runoff pattern from precipitation generated by a storm east of the Black Mountains. The corresponding erosion-deposition pattern is shown in Figure 15. The response of the modeled fan to waterbot diversion
depends on how much sediment is initially available in the main Gower Gulch channel just prior to diversion. If significant sediment had accumulated in the canyon channel by transport from hillsides prior to diversion, which is the case given the assumptions on sediment availability for this simulation, then the diverted flow first flushes out material from the main channel, causing a pulse of deposition on the proximal part of the fan, before finally incising the fan. The pulse of initial deposition is (barely) visible where it flanks the final channel incision in Figure 15. Large boulders derived from the Furnace Creek formation that now lie on the old fan surface near the canyon mouth may be evidence of such a depositional pulse (Sharp and Glazner, 1997).

Figure 13. Looking north across incised channel on upper Gower fan. The slopes of the incised channel bed and the original fan surface are highlighted. Jon Pelletier for scale.

Why incision occurred in the (linear) model can be seen by looking at the fan transport number $E_f$. Waterbots in Furnace Creek, which near the diversion point is an alluvial bedded stream, may be assumed to be carrying sediment at their transport capacity. The slope of Furnace Creek near the diversion point, $S_{c,Furnace}$ (about 1.5°), is less than the slope of the pre-diversion proximal Gower Gulch fan surface (which approaches 3° at the canyon mouth), Figure 16. Once the channel has been cleared of any excess alluvium, then $E_f = S_{c,Furnace} / S_{f,Gower} < 1$, i.e., the flow is under capacity and begins to erode fan material once it exits the canyon. In the model, incision is thus due to the enhanced transport capacity resulting from the steepness of the Gower fan relative to Furnace Creek, but other effects not included in the present simulation may also be important, such as nonlinearity of transport, temporal and spatial variations in precipitation intensity, and differences in grain size between Furnace Creek and Gower Gulch gravels. While flow nonlinearities may be present, the fact that Gower Gulch carries a greatly increased flow during Furnace Creek flood events need not in itself lead to fan incision. The flow debouching from the canyon mouth onto the Gower fan is laterally concentrated, but the flow entering the diversion point from Furnace Creek is also laterally concentrated, and about equally so (each channel is about 25-30 m wide both below and above canyon mouth and diversion point). Thus flow concentration is probably not greater on the proximal Gower Gulch fan than it is in Furnace Creek, and at least for the flows originating exclusively in the Furnace Creek drainage, would not tend to incise the Gower fan.

Figure 14. Precipitation from square “cloud” over part of Furnace Creek Wash runs through the otherwise dry Gower Gulch and onto fan. Coloration of stream paths is approximate. Streams have been artificially widened for better visibility.

Figure 15. Flows originating in Furnace Creek incise the Gower fan in this simulation. Incision occurs in this simulation because the proximal fan is steeper than the alluvial bedded Furnace Creek Wash near the diversion point. If significant runoff is contributed by the Gower Gulch drainage as well, then the fan may or may not incise, depending on the availability of hillslope regolith. In the simulation shown, “excess” alluvium in the Gower channel prior to the rainstorm is mobilized by the first waterbots down the channel, providing an initial pulse of deposition before incision begins. A remnant of this deposit is seen in the figure. In this simulation the von Neumann number is 0.033, and the thickness of pre-flow channel alluvium was 1 m.

The Gower Gulch gravels are finer, on average, than the Furnace Creek gravels, and perhaps more easily entrained. However, if the diverted flow is already at capacity, it is not obvious that, absent the steep fan surface, finer fan gravels could be easily added to the sediment load of floods debouching onto the fan.

Figure 16. Curves show slope along a single waterbot trajectory as it moves down Furnace Creek just prior to diversion (dark) and as it emerges onto the fan (light). Waterbot moves from left to right for each curve. The slope varies slightly as different waterbots make this journey, depending on their exact path and on the accumulation or deposition of sediment by prior waterbots. In general, Furnace Creek near the diversion point is slightly less steep than the proximal portion of the Gower fan, so that waterbots that reach the fan under conditions of poor sediment availability in the channel tend to be under capacity, and thus incise the fan.
Another cause of fan incision might be that floods that are too small to entrain Furnace Creek gravels may still be able to entrain finer Gower fan gravels. In one scenario, runoff like that shown in Figure 14 might be insufficiently powerful to entrain much Furnace Creek sediment, but nonetheless be able to entrain Gower Gulch and fan alluvium. However, the fact that Furnace Creek formation alluvium (originating in Gower Gulch) occurs in the low-slope reaches of the main channel of Gower Gulch, and has not been swept clear by Furnace Creek floods, suggests that enhanced occurrence of sediment-poor flows due to the Furnace Creek diversion is not primarily responsible for incision of the Gower fan.

12. SUMMARY

Waterbot models are members of a class of cellular automata models that simulate landscape erosion and deposition. Each waterbot moves autonomously and asynchronously across the landscape, independent of the behavior of other waterbots. Interaction between waterbots, which is necessary to mimic nonlinear sediment transport, is mediated through changes in cell properties (e.g., application of numerical pheromones) rather than by direct waterbot-waterbot interactions. This keeps model structure simple, i.e., waterbots interact with neighboring cells only, not directly with each other. This means that modifications to the model generally require only changes in the cell data base and the local rule-set.

The waterbot model is an example of a model that lends itself to a top-down formulation. Waterbot dynamics is an empirical dynamics that unfolds on the basis of rules and variables defined at the cell level. The waterbot algorithms need not be derived by appeal to the small scale physics of sediment transport, although they may be so-derived.

The waterbot model, like differential equation models, is based on the manipulation of a large number of degrees of freedom (cells or finite difference grid points, respectively). As conjectured above, if there is to be any succinct explanation for the behavior of a particular landscape system, it ought in general to be possible to construct a simple (few variable or few cell) model that incorporates what is known about that landscape, or the waterbot simulation thereof, and that replicates that behavior. If such a model cannot be found, then the simple explanation is likely to be wrong (or too succinct). If a model can be found, it is not necessarily correct, but it does provide a basis for a provisional improvement in ones prior understanding.

To illustrate its use, the waterbot model has been applied to erosion and deposition in the arid Black Mountains, California. For certain model assumptions, either continuing canyon deposition or incision of alluvial fans is indicated. Neither of these outcomes is observed today, suggesting that model assumptions need revision. A possible resolution is suggested that involves inclusion of fluctuations in storm intensity. The recent human-induced incision of the Gower Gulch fan via diversion of Furnace Creek is also analyzed using the waterbot model, with the conclusion, under model assumptions, that fan incision is probably due to the steepness of the original Gower fan surface rather than to the increased intensity of flow. Simulation results for the Black Mountains study area were also examined within the three-cell model provided by the appropriate dimensionless transport numbers.

Only the waterbot component of a general geological-agent model has been discussed at any length here. However, the concept of waterbot can be extended to the definition of other landscape agents that handle non-fluvial processes, such as debris flows, weathering, landslides and vegetation growth. Overall model landscape evolution is the result of the interaction of such agents or geobots. A model based on such discrete agents would have the same advantages of analogy to the physical system, uniform model structure, and ease of programming and interpretation as the waterbot model.

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