Spatial Erosion Rates in a Small Drainage Basin at Dynamic Equilibrium: An Experimental Study

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Abstract

How do drainage basins balance uplift with erosion over longer time scales? We address this problem by monitoring erosion in a small scale erosion facility. Our experimental drainage basin consists of an oval tank 1 m deep, 0.99 m long and 0.87 m wide. The substrate is mixture of silica flour (mean grain size 45 micrometers) mixed with 1 weight percent kaolinite to provide cohesion. A rainfall apparatus sprinkles fine mist over the surface, generating surface runoff that exits the basin at a motor-controlled outlet. These conditions allow a miniature drainage basin to develop and erode through a distance 3 to 4 times greater than the total relief of the basin. We conducted a series of runs at constant base level fall and rainfall rates, varied between runs. We find that constantly forced landscapes maintain characteristic regional slopes (roughly 10% temporal coefficient of variation at dynamic steady state) and constant statistical distributions of ridges and valleys. However, spatial erosion rates, determined by differencing gridded elevation data sets, depend strongly on the time scale over which the rate is determined. At short time scales of observation, large spatial variation in erosion rates exist (coefficients of variation of erosion rate are much greater than unity). The relation between spatial variability of erosion rate and time scale of observation in a power law, with an exponent of -2.3. Even at dynamic equilibrium, erosional processes within a drainage basin might not develop a uniformly eroding landscape.

Physical Model Setup

We begin each run by filling the basin with a 1:100 (by weight) mix of silica flour (silt size) and kaolinite. Rainfall and the outlet are turned on, and run continuously until the outlet reaches the floor of the basin. A dendritic stream network develops by headward erosion from the outlet. A balance between valley incision and erosion is reached roughly at the time of complete dissection of the initial flat surface. EroSSION processes include overland flow, channelized surface runoff and hillslope failures. We performed a series of runs, varying rainfall rate and uplift rate between runs. We captured time lapse video and digital stereophotographs, as well as water and sediment fluxes at the outlet. We extracted time series a gridded elevation models from stereophotographs for each run, and computed a suite of spatial landform statistics from the elevation models.

Experimental Results

A general result of numerical landform models based on surface runoff is that a landform will evolve to a stable form under steady forcing conditions of spatially uniform rainfall and uplift. A spatially stable form at constant uplift conditions implies spatially uniform erosion rates over the entire surface of the landform.

We designed a physical experiment to test this prediction. We constructed an oval basin, 100 cm long, 87 cm wide, and 100 cm deep. A sliding motor-controlled outlet dropped at a constant rate simulates spatially uniform uplift relative to base level. The depth of the basin is much greater than the instantaneous relief of the experimental landscape, thus allowing the landscape to evolve through several units of relief. Rainfall in the form of mist will generate runoff that exits the basin at the outlet.

We ran a series of numerical and physical experiments, and report below results from both. We note that the numerical simulations all evolve to a stable form.

Numerical Model Behavior

We encoded a simple erosion model based on steady state flow routing and hillslope diffusion. We calibrated the model input parameters to the area-slope relation in the physical experiment, and enforced the same boundaries as the physical experiment. We ran several simulations, extracted time series elevation grids, and computed spatial erosion rates for the numerical model at dynamic equilibrium.

Erosional variance of numerical model after dissection. While variance increases at shorter observation times, the variability is quite low.

Experimental landform statistics

We calculated general landform statistics from gridded elevation models of our miniature landscapes, and plotted them against a forcing parameter, r/U (rainfall rate / rainfall density / uplift rate * substrate density). Maximum relief, slope, and fractional area occupied by valleys are all sensitive to r/U.

Conclusions

If a landform is eroding uniformly, the coefficient of variation of erosion rate (standard deviation divided by average) should approach 1. We calculated the average and standard deviation of erosion rate on a cell-by-cell basis for all possible elevation model pairs after complete dissection. We normalized the time separation by the uplift rate (t/U), which yields a vertical separation distance between surfaces, and dividing by the maximum elevation (H) range at dissection. Thus, observation time is replaced with fractional eroded relief.

By plotting the coefficient of variation of eroded relief against erosion rate, we obtained a mean for spatial variability of erosion. We find that a power law relation exists between erosional variance and time scale of observation.

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