**Title:** Report on Physics of Channelization: Theory, Experiment, and Observation

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**Summary of results:** The investigations summarized in this final technical report were accomplished under Department of Energy, Basic Energy Sciences research grant number DE-FG0202ER15367 titled "Physics of Channelization: Theory, Experiment, and Observation," $197,172 from 09/15/2002 to 01/15/13. This work has focused on the coupling of groundwater flow to sediment transport, the evolution of topography in response to sediment transport, and the stability of channel heads to tip-splitting bifurcations in close collaboration with Professor Daniel Rothman of the Earth, Atmospheric, and Planetary Science Department at Massachusetts Institute of Technology.

The grant work over the course of the grant has resulted in nine peer reviewed scientific publications which are listed at the end of this report [1-9]. These publications can be freely accessed through a technical library or directly from the publisher for a nominal feel. The main results obtained during the last three year grant cycle are described in brief in the following.

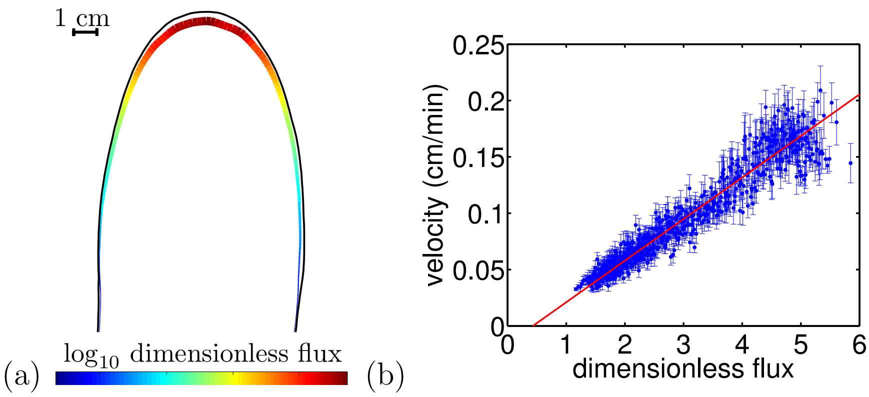


Figure 1: (a) The measured shape of the channel head (black line), and the magnitude of the flux as a function of position at the interface (color bar). (b) The velocity normal to the channel walls versus the flux of water into it shows that the channels grow linearly. The intercept implies that a finite flux of water is required for the channel walls to grow forward.

We first examined the growth and form of a kilometer-scale channel network in Bristol County, Florida which is considered to be an example of a seepage-driven network developed over millions of years in a sedimentary bed with a high infiltration rate that prevents surface runoff when it rains. The study build on field observations and two key postulated growth laws. First, the velocity with which a channel head advances is proportional to the groundwater flux flowing into it. Second, channel branching occurs proportional to the groundwater flux to the network. By reversing the dynamics for the advance of channel heads, we were able to estimate the age of the channel network and reconstruct the history of its growth. Further, we were able to predict the evolution of the characteristic length scale between channels, thereby linking network growth dynamics to geometric form. These results were published in Nature Geoscience [5].

At a closer scale, we then examined the detailed shape of the valley head shapes cut by groundwater flow emerging from springs that appear amphitheater-like. To better understand the origin of this topographic form we combined field observations, laboratory experiments, analysis of a high-resolution topographic map, and mathematical theory to quantitatively characterize a class of physical phenomena that produce amphitheater-shaped heads. The resulting geometric growth equation accurately predicts the shape of decimeter-wide channels in laboratory experiments, 100-meter wide valleys in Florida and Idaho, and kilometer wide valleys on Mars. We found that whenever the processes shaping a landscape favor the growth of sharply protruding features, channels develop amphitheater-shaped heads which can be described by a logarithm of a cosine form with an aspect ratio of $\pi$ (see Figure 1a). These results can be also used toward the interpretation of such valley heads on Earth and Mars, and were published last year in the Journal of Fluid Mechanics [6].

We then investigated the relation between the local channel interface growth rate and the flux of water into the channel head with experiments to test one of the postulates regarding curvature related growth. A hydraulic head is used in the experiments to push water through an inclined sand bed. As water flows out of the sand bed, it entrains grains, thus forming a seepage channel. Using a laser-aided topography technique, we measured the elevation contour which is shown in Figure 1(a). The velocity was measured from changes in the shape and position of the channel in the experiment and the flux by solving the Laplace equation around the measured shape of the channel. As shown in Figure 1(b), the velocity at which the channel grows outward is linearly related to the flux of water into it. This is unexpected, as typical transport relationships relate sediment transport to shear nonlinearly. Further, the intercept of this relationship is negative according to the least-squares fit of the data meaning that a finite flux of water is required for the channel wall to grow forward. Because the growth of the channel requires that sediment be transported through the channel, this relationship between flux and growth does not reflect a simple force balance on a sand grain. Rather, it arises from the coupling between sediment transport within the channel and subsurface flow around the channel. It is therefore remarkable that this relationship takes a form in which the growth at a point depends only on the flux at that point. These results were published in Comptes Rendus Geoscience [7].

Along with these studies, we systematically investigated erosion patterns observed in a horizontal granular bed resulting from seepage of water, with an experimental apparatus consisting of a wide rectangular box filled with glass beads with a narrow opening in one of the side walls from which eroded grains can exit. Quantitative data on the shape of the pattern and erosion dynamics were obtained with a laser-aided topography technique. We showed that the spatial distribution of the source of groundwater significantly impacts the

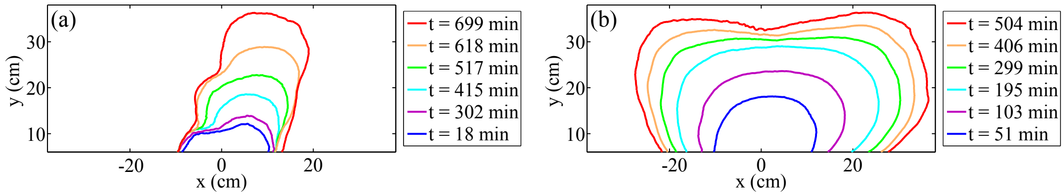


Figure 2: Examples of channels observed when the ground water is fed at the top boundary (a) and when it is fed by uniform rainfall on the bed (b). The channel is observed to bifurcate in the case where the ground water is sourced by uniform rainfall.

shape of observed patterns (see Figure 2). An elongated channel is observed to grow upstream when groundwater is injected at a boundary adjacent to a reservoir held at constant height. An amphitheater shape is observed when uniform rainfall infiltrates the granular bed to maintain a water table. Bifurcations were observed as the channels grow in response to the split in the ground water flow (see Figure 3). We further found that the channels grow by discrete avalanches as the height of the granular bed is increased above the capillary rise, causing the deeper channels to have rougher fronts. The spatio-temporal distribution of avalanches increased with bed height when partial saturation of the bed leads to cohesion between grains. However, the overall shape of the channels was observed to remain unaffected indicating that seepage erosion is robust to perturbation of the erosion front. A manuscript reporting these results was published in Physical Review E [9].

# References

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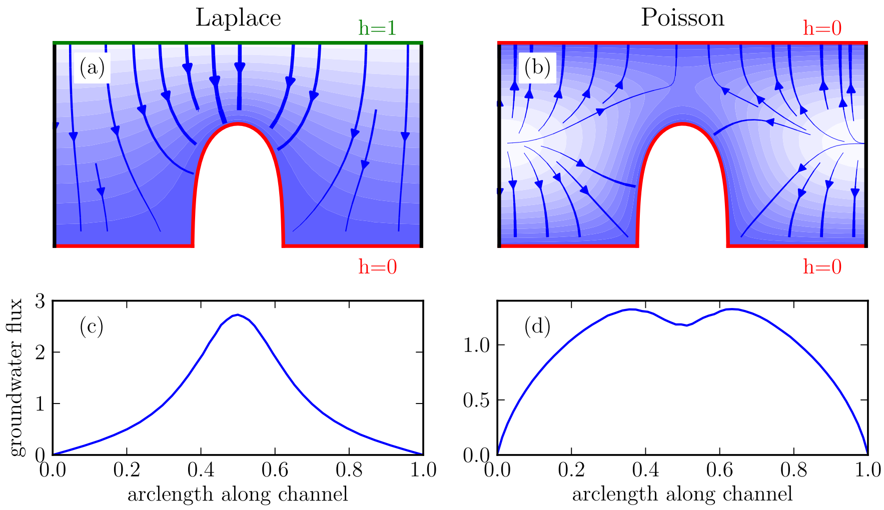


Figure 3: The differences of ground water distribution in the Laplace (a) and Poisson (b) equations lead to differences in the water arriving at the channel interface. A single peak is observed in the case of Laplace which leads to a finger like growth, whereas a double peak is observed after the channel has grown long enough in the Poisson case corresponding to rainfall as in Figure 2(b).

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