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Application of an evolutionary algorithm for parameter optimization in a gully erosion model

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ABSTRACT

Herein we demonstrate how to use model optimization to determine a set of best-fit parameters for a landform model simulating gully incision and headcut retreat. To achieve this result we employed the Covariance Matrix Adaptation Evolution Strategy (CMA-ES), an iterative process in which samples are created based on a distribution of parameter values that evolve over time to better fit an objective function. CMA-ES efficiently finds optimal parameters, even with high-dimensional objective functions that are non-convex, multimodal, and non-separable. We ran model instances in parallel on a high-performance cluster, and from hundreds of model runs we obtained the best parameter choices. This method is far superior to brute-force search algorithms, and has great potential for many applications in earth science modeling. We found that parameters representing boundary conditions tended to converge toward an optimal single value, whereas parameters controlling geomorphic processes are defined by a range of optimal values.

Software availability

Name of software: GullyErosionProfiler1D
Developer: Francis Rengers
Contact address: U.S. Geological Survey, 1711 Illinois St., Golden, CO 80401. frengers@usgs.gov
Year first available: 2012
Required software: Matlab
Source: https://github.com/csdms-contrib/gullyerosionprofiler1d
Availability and cost: GNU licensed freeware
Name of software: $Param_{scan}$
Developer: Monte Lunacek
Contact address: National Renewable Energy Laboratory, 15013 Denver W, Pkwy, Golden, CO 80401. Monte.Lunacek@nrel.gov
Year first available: 2014
Required software: Python
Program Language: Python
Source: https://github.com/frengers/JanusOpt/tree/master/src
Availability and cost: GNU licensed freeware

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1. Introduction

Landscape change results from erosion and sedimentation processes that govern mass redistribution over long time periods; consequently, direct observation of landscape evolution is rarely possible. In order to properly understand how different geomorphic processes and landscape properties influence long-term erosion it is necessary to use models as proxies for large-scale landscape evolution. In most scenarios it is infeasible to construct physical models (Tucker, 2009) because important properties (such as rain-drop size) do not scale with model landscapes. As a substitute for direct observation, computer models serve as a useful alternative (Tucker and Hancock, 2010).

Computational landform evolution models are composed of geomorphic transport laws (GTLs) (Dietrich et al., 2003), and a key challenge for computer modeling is choosing model parameter values for the GTLs. Parameters such as soil/rock erodibility are difficult to measure (Elliot et al., 1989; Prosser and Dietrich, 1995), therefore there is large uncertainty in the values assigned to these parameters. It is common to use steady and uniform values for some fluxes such as soil infiltration, which can presumably be estimated from field measurements; however, point infiltration rates can vary by orders of magnitude within the same watershed (Sharma et al., 1980). Consequently, process parameter values are often estimated by calibration (e.g. Barkwith et al. (2015)), which in turn requires comparison between observed and predicted landscape properties. Moreover, there is uncertainty in the initial and boundary conditions. Here we explore the use of optimization techniques to search for input values for these uncertain model parameters.

In this study, we have focused on a model of gully erosion. Gullies are deeply incised channels that migrate upstream via erosion from near-vertical headcuts, which are analogous to waterfalls in rivers (Fig. 1). Water erosion in the model works to incise the gully vertically, and headcuts migrate upstream as they erode. The model was developed to explore how the processes of headcut erosion and water incision compete to form a concave-up longitudinal profile while maintaining a near-vertical headcut over hundreds of years (Rengers and Tucker, 2014). Our model, and the range of parameter values used in the model, are based on observations from the West Bijou Creek study site in eastern Colorado (Rengers and Tucker, 2014, 2015).

We applied the Covariance Matrix Adaptation Evolution Strategy (CMA-ES) (Hansen and Ostermeier, 2001), a parameter optimization scheme, to determine the most appropriate model parameter values. This approach is an inverse modeling method in which a model is run with different input parameters, and model output is subsequently compared to a known observed value. The best model parameters are determined as those that provided the closest fit between the model output and the observations.

2. Background

The overall longitudinal profile of a gully results from the competition between fluvial erosion and sedimentation processes (Rengers and Tucker, 2014). These processes are conceptualized in Fig. 2. Wall failure as shown in the conceptual model can result from a variety of processes including: ground water seepage (Howard and McLane, 1988), piping (Verachtert et al., 2010), direct wash erosion over headcut walls (DeLong et al., 2014), mass failure (Bradford and Piest, 1980; Dietrich and Dunne, 1993; Istanbulluoglu et al., 2005; Montgomery, 1999), and plunge pool erosion through undercutting (Gardner, 1983; Gilbert and Hall, 1907; Stein and LaTray, 2002; Wohl et al., 1994). At our specific study site headcut wall failure was primarily associated with mass failure via soil saturation resulting from overland flow (Rengers and Tucker, 2015). Regardless of the specific process that governs headcut wall failure, erosion at the headcut has the ability to dramatically alter the overall profile of a gully over time depending on the rate of wall failure, and the influence of fluvial erosion (Gardner, 1983; Stein and Julien, 1993; Rengers and Tucker, 2014).

Three scenarios demonstrate the end-member possibilities required to dynamically maintain a gully headcut (Fig. 3). First, if headcut wall failure occurs at a high rate, but fluvial processes are unable to transport the material away from the toe of the headcut; the headcut will become buried and a section of the gully channel will become locally convex (Fig. 3a). Alternatively, if fluvial erosion operates at a high rate, eroding both the headcut lip and sediment deposited by headcut wall failure, then the gully channel will become locally concave (Fig. 3b). Neither of the prior scenarios would preserve a discrete headcut step. A headcut is only preserved in the unique situation where fluvial erosion upstream of the headcut is limited and fluvial erosion downstream of the headcut is sufficient to remove material deposited from headcut wall failure (Fig. 3c). This conceptual view of gully longitudinal profile evolution has been implemented in a numerical model in order to quantitatively test the hypothesis proposed in this conceptual framework (Rengers and Tucker, 2014).

2.1. Study site

The gully erosion model is based on observations from a gully system that drains to West Bijou Creek on the high plains of eastern Colorado, USA (Rengers and Tucker, 2014, 2015). The underlying geology at the study site is a sequence of poorly lithified sandstone and shale units of Cretaceous to early Paleogene age (Barclay et al.,

Fig. 1. View of a headcut migrating upstream and extending gully erosion.