Application of a model for point-wise prediction of stream flow statistics using climatic and geomorphologic data to Taiwan

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Introduction

Fluvial erosion controls the shape of many mountain belts. Much effort has been put in understanding how climate, and in particular, the patterns of rainfall affect river discharge and thus fluvial erosion. In particular, it is important to develop a better understanding of the link between rainfall variability and mean, and discharge variability and mean in mountainous river catchments in order to build predictable models of long-term geomorphic evolution of mountain belts, but also to predict the magnitude and frequency of natural hazards (e.g. landslides, floods).

Currently, our understanding is limited by the assumption of uniformity of rainfall mean and variability in any catchment, which is often not the case in mountainous river catchments where the control of rainfall by orography cannot be neglected, as both mean rainfall intensity and variability vary greatly with altitude and continentality. The main focus of the work presented here is to answer these questions, i.e. to overcome these severe limitations, and to improve current models of the relationship between rainfall and discharge characteristics by taking into account orographic effects on precipitation, as well as the effect of finite storm size in large catchments. Ultimately, our work can be used to predict how these forcings affect erosional processes when they are characterized by a threshold, such as river incision or landsliding.

Previous work

Tucker [1] introduced a method for modeling long-term erosion and sediment transport rates which combines the joint effects of thresholds with a stochastic (frequency-magnitude) representation of climatic forcings. They suggested that the existence of a threshold in the erosional system introduces non-linearities which have a first-order effect on, among other things, the sensitivity of erosion rates to climate variability, and are the most noticeable in high threshold systems. Lague et al. [2] confirmed the findings of Tucker [1] about the influence of short-term variability and thresholds on long-term erosion rates, and found that the variability is important when the incision threshold is high compared to the incision rate and/or incision law is non-linear with respect to shear stress, by using a different approach in the selection of the discharge magnitude-frequency distribution, allowing for greater importance of extreme events than Tucker ([2]. Furthermore, they derived an analytical solutions for the long-term incision rates. They showed that the relative importance of mean and variability in discharge, in terms of the rates, can be split into three regimes in relevance to the return times of critical (erosive) discharge. Moreover, they predicted a power-law relationship between slope and incision rate with the exponent independent of the incision-shear stress exponent, but sensitive to runoff variability and channel cross-sectional geometry. Rossi et al. [3], due to commonly observed heavier tailed distributions of runoff compared to rainfall, explored hydrologic and climatic controls on the runoff variability in the contiguous USA, in order to identify the causes for the difference in the shape of the tails of rainfall and runoff distributions. They arrived to the conclusion that because of the dynamical non-linearity of the hillslope-scale runoff response, the transformation from rainfall to runoff is (strongly) non-linear (in arid conditions) with decreasing non-linearity towards more humid conditions. The key parameters controlling the degree of runoff variability being mean annual evapotranspiration (ET) ratio, aridity index and the ratio of wet to dry days, instead of rainfall statistics (mean and variability) which are of second-order influence on the variability. Deal [4] demonstrated that a probability density function (PDF) of discharge can be derived from a probability density function of rainfall using only two parameters characterizing the response of a given catchment to a pulse in rainfall: the response time of the catchment, τ, and and exponent, a, characterizing the nonlinearity of the response of the catchment. Depending on the value of the exponent a, the probability density function of discharge takes the form of a gamma distribution ($a = 1$) or an inverse gamma distribution ($a = 2$).

Most existing models rely, however, on the assumption that rainfall characteristics are uniform over a given catchment. This is clearly not the case for many mountainous catchments which are affected by orographic control on precipitation or for catchments that are much larger than the average storm size.

Method

We have used the same stochastic, analytical model as used by Deal [4] and developed by Botter et al [5] that is based on catchment-scale soil water balance forced with stochastic rainfall, modeled, at daily timescale, as a marked Poisson process with average frequency λ_p and exponentially distributed depths with average α. This implies that the dynamics of stream flow is a reflection of effective rainfall events that fill the water deficit in the root zone, also modeled as a marked Poisson process, with frequency λ ($\leq \lambda_p$), followed by power law recessions (as implied by non-linear storage-discharge relationship) lasting until the next event. The recessions are characterized by a coefficient $K = 1/\tau$ and an exponent a, describing the discharge recession equation $\frac{dQ}{dt} = -KQ^a$. An analytical expression, used in the model, for the prediction of discharge PDF is defined by four physically based parameters (which reflect different climatic, hydrologic and geomorphic characteristics of the catchment) that are the mean rainfall depth (α), the frequency of flow producing rainfall events (λ), the recession coefficient (K) and the exponent (a). We have also use the geomorphic recession flow model developed by Biswal and Marani [6] and further improved by Doulatyari et al [7] that uses a topographic DEM to estimate the geometry of the drainage network and its evolution through time to compute discharge variability at various points along the drainage network.

The four main model parameters are estimated at every point along the river network using climatic and geomorphic data as input, and, when possible and necessary, gauge data from the nearby catchment(s) for the calibration and validation of the model. The model requires Potential Evapo-Transpiration (PET) data that can be obtained from two sources: (1) global maps with a spatial resolution of 1 km^2 and temporal of 1 month, and (2) estimated (using Penman-Monteith equation) from daily weather data which was received, along with gauge data, from the Taiwanese weather organization. The 30m DEM data, used for the estimation of river topology was obtained from global DEMs obtained from USGS.

Daily rainfall data observed at a finite set of stations was interpolated and used to create grids of rainfall statistics in the contributing area. Rainfall frequency λ_p was estimated as the ratio of wet to total number of days, and along with cumulative rainfall field used to estimate mean rainfall depth (α), as the ratio $\frac{P}{\lambda_p}$. The frequency of effective rainfall events was obtained by means of (calibrated) water balance models, used for the estimation of the runoff coefficient ϕ, and consequently for the prediction of the frequency of flow producing events (λ), through the relation $\lambda = \phi\lambda_p$. The recession exponent a and coefficient K were estimated using DEM analysis and GRFM model, which exploits the idea that the time evolution of the active drainage network is connected to the fluctuations in stream flow, in particular, the exponent a is determined with the least square method between the length of active drainage network, $G(l)$ and the number of links at the distance l from the outlet, $N(l)$, which are both derived from the DEM analysis. The coefficient K is estimated through its functional dependency on mean rainfall depth, frequency of effective events, recession exponent and θ (a constant depending on the speed of drainage network contraction).

Results

We show that, using this model, we can predict with reasonable accuracy discharge variability observed at various gauging stations in a catchment that is affected by a strong orographic gradient. We are currently working on applying this method to other areas.

References

[1] G. E. Tucker *Drainage basin sensitivity to tectonic and climatic forcing: implications of a stochastic model for the role of entrainment and erosion thresholds*, Earth Surface Processes and Landforms, 29(2), 185-205, doi:10.1002/esp.1020, (2004).

[2] D. Lague et al. *Discharge, discharge variability, and the bedrock channel profile*, Journal of Geophysical Research: Earth Surface (2003-2012), 110(F4), doi:10.1029/2004JF000259, (2005).

[3] M. W. Rossi et al. *Precipitation and evapotranspiration controls on daily runoff variability in the contiguous United States and Puerto Rico*, Journal of Geophysical Research: Earth Surface, doi:10.1002/2015JF003446, (2016).

[4] E. Deal. *A probabilistic approach to understanding the influence of rainfall on landscape evolution*, what to put here? PhD thesis? (2017).

[5] G. Botter et al. *Basin-scale soil moisture dynamics and the probabilistic characterization of carrier hydrologic flows: Slow, leaching-prone components of the hydrologic response*, Water Resour. Res., 43, W02417, doi10.1029/2006WR005043, (2007).

[6] B. Biswal and M. Marani. *Geomorphological origin of recession curves*, Geophys. Res. Lett., 37, L24403. doi:10.1029/2010GL045415, (2010).

[7] B. Doulatyari et al. *Patterns of streamflow regimes along the river network: The case of the Thur river*, Environmental Modelling and Software, 93, 42-58, (2017).