A Blueprint for an Integrated Watershed Hydrogeomorphic Modeling System

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Abstract

The hydrology of a river basin interacts with its geomorphic form. Despite significant advances in hydrological modeling, the dynamic interactions between geomorphic, hydrologic and ecological processes are not adequately captured at the basin scale. There is a need for advanced modeling tools that address both runoff and erosion prediction in sufficient spatial and temporal detail for exploring process couplings, feedbacks and complexity.

In this paper we present a blueprint for integrating the Channel-Hillslope Integrated Landscape Development (CHILD) and TIN-based Real-time Integrated Basin Simulator (tRIBS) models in a hydro-eco-geomorphic framework where process interactions and feedbacks are characterized. The integration of these models opens new avenues to explore the topographic, vegetative and climatic controls on watershed process interactions. Here, we present the capabilities of the two models and discuss a strategy for model integration. We also provide an example of the erosion effect on thunderstorm runoff response in a semi-arid basin as a proof-of-concept for model integration.

Keywords: distributed modeling, watershed, hydrology, erosion, vegetation, tRIBS, CHILD

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Introduction

Catchment hydrology depends on the geomorphic form of the basin and the hillslope, channel and ecological processes active at different spatial and temporal scales (Osterkamp and Toy 1997, Tucker and Bras 1998). The long-term river basin evolution is linked with the underlying mechanisms of hydrologic response, while the short-term storm response depends on topographic variability resulting from erosional processes. For example, gully erosion may increase drainage density, affect runoff generation and contribute to the formation of rapid runoff hydrographs (Ritter and Gardner 1993). Similarly, erosional perturbations can impact soil moisture distribution and vegetation growth, which can have important implications on hydrology.

Numerical models typically treat hydrologic and geomorphic processes independently due to differences in response time scale. Recent process-based erosion models, such as KINEROS (Woolhiser et al. 1990), EROSION 3D (Schmidt et al. 1999) and CASC2D (Ogden and Heiling 2001) simulate hydrology and use flow predictions for sediment transport. We think this approach is valid for "geomorphic equilibrium" when an approximate balance exists between soil production and removal by erosion. This period of equilibrium is often interrupted by external factors such as extreme climate events, disturbances and land-use change or by internal factors such as the exceedence of process thresholds (Schumm 1980). Erosional response to such changes can be quite rapid and have large impacts on the catchment hydrologic response.

The objective of this paper is to present and illustrate a hydrogeomorphic framework for continuous runoff and erosion modeling where interactions and feedbacks between hydrologic response and geomorphic form are explicitly characterized. We focus on the fluvial erosion of a small catchment in the Walnut Gulch Experimental Watershed. A disturbance regime due to climate variability and/or vegetation shifts is imposed on the current

topography to induce erosional response in the channel network (i.e. propagation of an erosion wave) and on hillslopes due to rill incision. Short-term hydrologic response to summer thunderstorm events is then analyzed in the context of the evolving landscape. It is hypothesized that fluvial incision leads to increases in the drainage density that causes an intensification of the runoff response.

In the following sections, we discuss the framework for coupling the two distributed models for landscape evolution (CHILD) and continuous runoff prediction (tRIBS). The models currently share a computational platform and basin partitioning using a triangulated irregular network (TIN), but have yet to be utilized in a conjunctive fashion. This study is a preliminary investigation into the coupled use of the two modeling tools. In so doing, we outline a "blueprint" for model integration and illustrate its potential by addressing the effect of erosion on surface hydrologic response within a well-instrumented research catchment.

Integrated Hydrogeomorphic Modeling

Figure 1 presents the hydrogeomorphic processes represented in the integrated model. Basin storm and interstorm periods force an erosional, hydrologic and vegetative response which are both defined by and have an influence on the basin geomorphic and landuse properties. In the following, we discuss the elements of the model blueprint and their integration.

Triangulated model framework

The TIN data structure utilized in the two models is a surface representation defined by triangular elements of varying size. Tucker et al. (2001a) describes the data structure and geometry of the irregular mesh. Various factors motivate their use in basin modeling. The primary advantage is the variable resolution obtained through the irregular spacing of elevation nodes, which translates to computational savings. A second advantage is that TINs permit streams and boundaries to be preserved. In addition to the TIN, a Voronoi mesh is associated with the model domain. A unique set of Voronoi polygons is created by intersecting the perpendicular bisectors of each triangle edge (Tucker et al. 2001a). These irregular polygons surround a TIN node and form the basis for finite-volume computations in the two models.
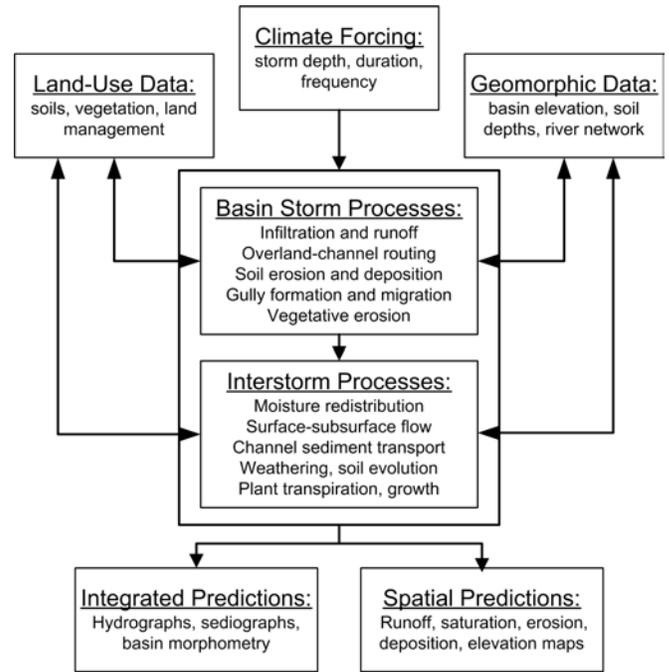

Figure 1. Integrated hydrogeomorphic model blueprint.

Landscape evolution: The CHILD model

The CHILD model simulates basin-scale changes in landscape morphology resulting from tectonic, channel and hillslope processes. The model incorporates climate forcing, steady-state runoff production, fluvial erosion and deposition, soil evolution due to soil creep and bedrock weathering, floodplain deposition, meander evolution, and a simple vegetation model (Tucker and Bras 2001, Tucker et al. 2001b). In the fluvial erosion component used here, the rate of change of elevation (z) is the difference between tectonic displacement (U) from either uplift or base level lowering and local erosion (E), as:

$$\frac{\partial z}{\partial t} = U - E = U - \begin{cases} \nabla \bullet Q_s \\ E_c \end{cases} \quad (1)$$

where Q_s is the sediment transport rate, E_c is an erosion capacity and ∇ is the divergence operator. The erosion term can be modeled using two general types of erosion postulates: transport or detachment limited. The first postulate (the upper term in 1) dictates the conservation of mass, and erosion is represented as the difference between sediment outflux and influx. In the latter erosion law, the rate of local incision is assumed to depend on local shear stress or stream power.

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The reader is referred to Tucker et al. (2001a, 2001b) for details on the various geomorphic processes simulated in CHILD. Currently, additional modules that simulate shallow landsliding, debris flow transport and gully erosion processes involving plunge-pool erosion, bank failures and sapping are being added to the model.

Distributed hydrology: The tRIBS model

tRIBS is a physically-based distributed hydrologic model designed for real-time, continuous forecasting. Over the TIN terrain, the model uses rainfall and meteorological forcing to predict basin response, including infiltration, runoff, evapotranspiration, soil moisture and aquifer recharge. Ivanov et al. (in review) provide detailed descriptions of the model, including the parameterizations for coupled unsaturated-saturated dynamics, runoff production and routing, and moisture redistribution through the hillslope system.

At the heart of the tRIBS model is a simplified, coupled system of equations leading to infiltration, lateral moisture fluxes and groundwater recharge. The sloped, heterogeneous, anisotropic soil column is characterized by a vertical decay in hydraulic conductivity (K_n):

$$K_n(z) = K_s e^{-fz} \qquad (2)$$

where f is the conductivity decay parameter. Horizontal conductivity (K_p) is accounted for via an anisotropy ratio ($a_r = K_n / K_p$). Ponded and unsaturated infiltration are taken into account. The interaction between propagating moisture fronts, water table fluctuations and lateral moisture exchanges leads to various runoff mechanisms produced within each model element:

$$R = R_I + R_S + R_P + R_G \qquad (3)$$

where R_I is infiltration-excess runoff, R_S is saturation-excess runoff, R_P is perched return flow and R_G is groundwater exfiltration. The water table position determines the hydrostatic soil moisture profile in the unsaturated zone, which in turn controls the runoff partitioning. Routing of surface flow is achieved via overland and channel pathways through a hydrologic hillslope and hydraulic channel routines. The channel geometry is derived from a geomorphic relation:

$$W = \alpha A^\beta \qquad (4)$$

where W is the channel width, A is the contributing upslope area, and α and β are parameters (Table 1).

Blueprint for model integration

Our strategy for integrating CHILD and tRIBS consists of loosely coupling the models through common landscape variables to simulate basin processes at both short (years to decades) and long term (up to millennia) time scales (Figure 1). Both models share the same TIN architecture and C++ object-oriented code structure. However, because the models focus on distinct basin processes operating over different times, they are executed at different time steps. For example, the CHILD time step is based on the duration of erosive storms (days – years), whereas tRIBS utilizes shorter time steps based on rapid unsaturated-saturated fluxes (minutes – hour). If tightly coupled by resolving all processes at a high temporal resolution, the resulting model would require a high computational demand. To increase efficiency, our strategy is to couple the two models through an adaptive time sequencing scheme for both short and long-term simulations.

For short-term simulations, we will incorporate the existing sediment transport algorithms in CHILD into the tRIBS model. This will permit hydrograph and sediograph predictions within the basin. To explore long term changes, such as climate variability or vegetation shifts, we will loosely couple the models by interchanging landscape state variables, which will translate the effects of geomorphic dynamics onto basin hydrology. We identify the important state variables as: topography, drainage density, soil depth, vegetation pattern and type, and stratigraphy. Over decades or centuries, CHILD could evolve these states through various geomorphic processes, while tRIBS could use these predictions to explore the hydrologic implications of basin evolution. This "magnifying" approach would add to our understanding of landscape process interactions and feedbacks across various time scales.

Illustrative Example

Here we present an example of the magnifying approach to coupled hydrogeomorphic modeling in a real world watershed. We impose fluvial erosion on an existing topography and explore the hydrologic consequences as an erosion wave propagates to the headwater channels. In the following, we describe the study area and the design of our numerical

experiment, followed by the hydrogeomorphic simulations results.

Study area

To illustrate the coupled prediction of fluvial erosion and runoff, we selected a 2.27-km^2 subwatershed of the 149-km^2 USDA-ARS Walnut Gulch Experimental Watershed located in southeast Arizona (Figure 2). The basin topography, obtained from a 28.6-m USGS digital elevation model (DEM), is represented through a high-resolution triangulated irregular network. The hydrographic TIN model (3,600 nodes) captures terrain variability, and explicitly represents the basin boundary and embedded stream network (Vivoni et al. 2003).
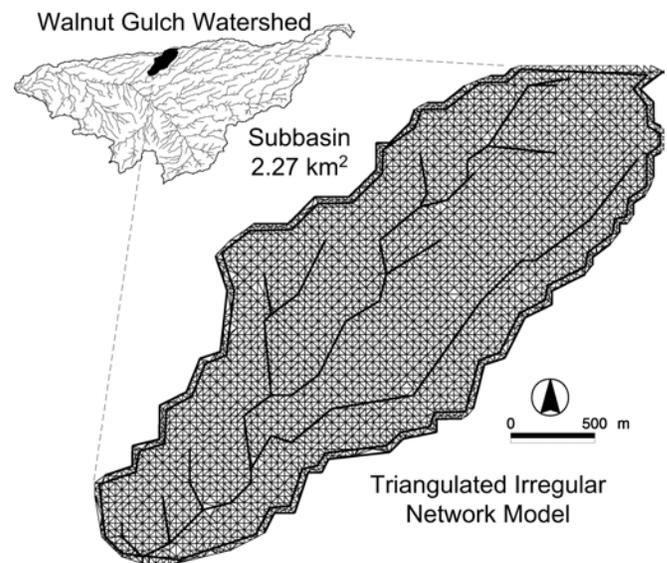

Figure 2. Initial TIN terrain model for study area with basin boundary and channel network.

The semi-arid basin is characterized by desert shrub vegetation and very gravelly, sandy loam soils (Houser et al. 2000). High-intensity, short-duration convective rainfall from summer thunderstorms produces the majority of the observed runoff measured at the outlet via a flume (W-4) (Syed et al. 2003). Infiltration-excess runoff is the primary mechanism due to the deep water table position and low soil infiltration capacity. Given the small basin area, spatially-uniform surface and rainfall conditions are assumed here. Only the spatial distribution of the evolving landscape topography impacts the runoff and erosion response in the catchment. These assumptions can be relaxed in the current framework, as shown by Ivanov et al. (in review). Table 1 lists the model parameters obtained from field and

modeling studies (Grayson et al. 1992, Goodrich et al. 1997, Miller et al. 1996, Hernández et al. 2000).

Table 1. Uniform basin parameter values.

Parameter	Value
Saturated conductivity (K_s)	8.5 mm/hr
Soil porosity (ε)	0.45
Saturation soil moisture (θ_s)	0.41
Residual soil moisture (θ_n)	0.04
Conductivity decay (f)	0.007 mm^{-1}
Anisotropy ratio (a_r)	100
Vegetation cover (v)	0.1
Manning roughness (n)	0.3
Geomorphic width coefficient (α)	7.24
Geomorphic width exponent (β)	0.34
Erodibility (k_e)	3.7×10^{-4} (kgs^{-1}m^{-2}Pa^{-P})
Excess shear stress exponent (p)	2.3
Storm duration (t_d)	1 hr
Rainfall intensity (i)	100 mm/hr
Interstorm duration (t_r)	60 hr

Experimental design

To demonstrate the potential for coupled modeling, we simulate the geomorphic processes associated with fluvial erosion and then its impact on watershed hydrologic response. In this study, CHILD and tRIBS are loosely tied via a common modeling framework and exchange of topographic data. The USGS DEM is utilized as an initial terrain condition. Operating over a long sequence of storm-interstorm periods, the hillslope and channel processes in CHILD lead to erosion throughout the basin. The initial topographic condition and a final instance of landscape evolution after 100 storms are then ingested into the tRIBS model to produce comparative runoff responses. The evolving geomorphic form will impart different signatures on the basin hydrograph and runoff spatial pattern.

Erosion

Fluvial erosion is modeled using (1) based on detachment limited erosion (Tucker et al. 2001b). The erosion rate is related to shear stress (τ) acting on soil grains in excess of a threshold (τ_c) as:

$$E_c = k_e \left(\tau - \tau_c \right)^p, \quad \tau = k_t q^{0.6} S^{0.7} > \tau_c \qquad (5)$$

where k_e is soil erodibility, and k_t relates shear stress to discharge (q) and slope (S) and is a function of soil

roughness and channel shape (Istanbulluoglu et al. 2003). We obtained a value for k_t using the current topography of the study basin. Geomorphology literature suggests that unless an external disturbance is imposed, erosion is due to runoff rates (R) which recur every two years and at least once in five years (Wolman and Miller 1960).

Based on our hydrology simulations described next, a 2-year runoff rate, R has a magnitude of 70 mm/hr in this basin. Making the steady-state assumption of $q = R*a$, where a is the specific catchment area, and using $\tau_c = 5$ Pa (sediment diameter of 6 mm), a k_t value of ~500 produced limited erosion around the basin outlet. To simulate erosion due to external factors, we increased k_t by a factor of 5. Such an increase mimics a full scale disturbance of vegetation and/or an implicit increase in runoff rate due to higher rainfall (i.e. climate change). For comparison, Istanbulluoglu et al. (2002) found a factor of 3 difference in k_t between a forested and a partially burned basin in Idaho.

We used values for k_e and p in (5) (Table 1) reported by Nearing et al. (1999) for a site close to the study basin. Given these parameter values, we found that the selected runoff rate ($R = 70$ mm/hr) results in erosion that occupies the entire catchment, from outlet to headwaters, within a series of 100 thunderstorms (see next section). Within this period, CHILD simulates an erosion wave commencing in the basin lowlands and traveling upstream. In so doing, the propagating wave influences channel elevations throughout the network and leads to adjustments in the hillslope profiles. Upon reaching all basin locations within the specified erosion threshold, a stable state is reached in the elevation field. We test the hydrologic sensitivity of the initial and final landscapes in the following (Figure 3).

Thunderstorm runoff

Thunderstorm rainfall is modeled as a series of discrete random events separated by interstorm periods. The storm sequence is generated by sampling an exponential distribution constructed for the storm duration (t_d), intensity (i) and interstorm duration (t_r). Table 1 lists the storm parameters used for summer conditions in the basin (Chagnon 1998). Due to high rain rates over the gravelly sandy loam soil, infiltration excess runoff is the primary runoff mechanism. Prior to each simulation, the water table depth is set to a deep uniform value that determines the initial moisture profile (Ivanov et al. in review). A

spin-up period of several months is allowed to minimize initialization errors. Subsequently, a one-month rainfall-runoff simulation is conducted. No plant interception or evapotranspiration are simulated as we concentrate on the runoff response to intense storms capable of eroding the land-surface.
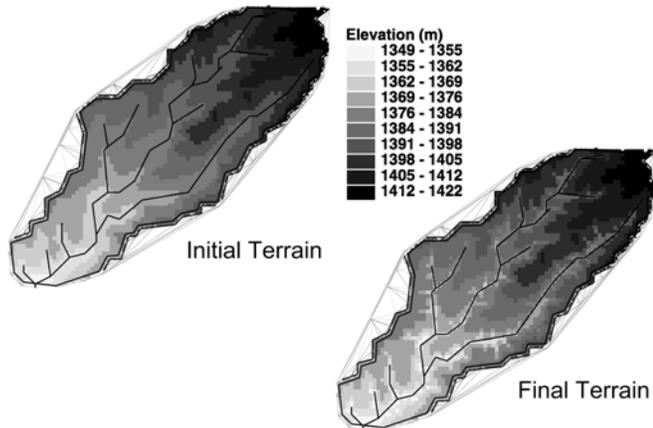

Figure 3. Evolving landscape elevation at initial and final time periods.

Figure 4 presents a runoff hydrograph comparison for the terrain models for two storm events. These cases represent two interesting scenarios. In Day 16, two individual, closely-spaced, storms produced a dual peak runoff response. In Day 25, a single peak event of large magnitude occurring after a long interstorm period produced a significant flood event at the basin outlet. Note that the runoff response to the same applied rainfall varies for each terrain. As the erosion wave advances, the flood peak increases in magnitude and decreases in response time, suggesting higher basin sensitivity to rainfall. Fluvial erosion leads to higher slopes along the hillslope-channel interface that affect the hydrograph. The overland flow velocity increases as well since it is tied to the channel discharge in the nearest stream link in the model. As erosion progress into hillslope regions, increased slopes also lead to higher lateral transport of the unsaturated zone moisture that also accelerates basin response.

While the hydrographs are indicative of the integrated catchment response, they do not provide information on the spatial distribution of runoff generation. Figure 5 presents a means for capturing these spatial patterns. Here, the temporal frequency of infiltration-excess runoff (R_I) (i.e. fraction total time), the primary mechanism occurring in the basin, is shown for the initial terrain model. Note that runoff is produced frequently within the channel network

and along hillslope hollows. This is due both to rainfall rates exceeding the normal hydraulic conductivity (K_n) and lateral moisture transport in the unsaturated zone, which occurs due to the high anisotropy ratio (a_r). This preferential lateral flow in the absence of a high water table is plausible in soil horizons characterized by an exponential decrease in K_n (e.g. Beven 1982).
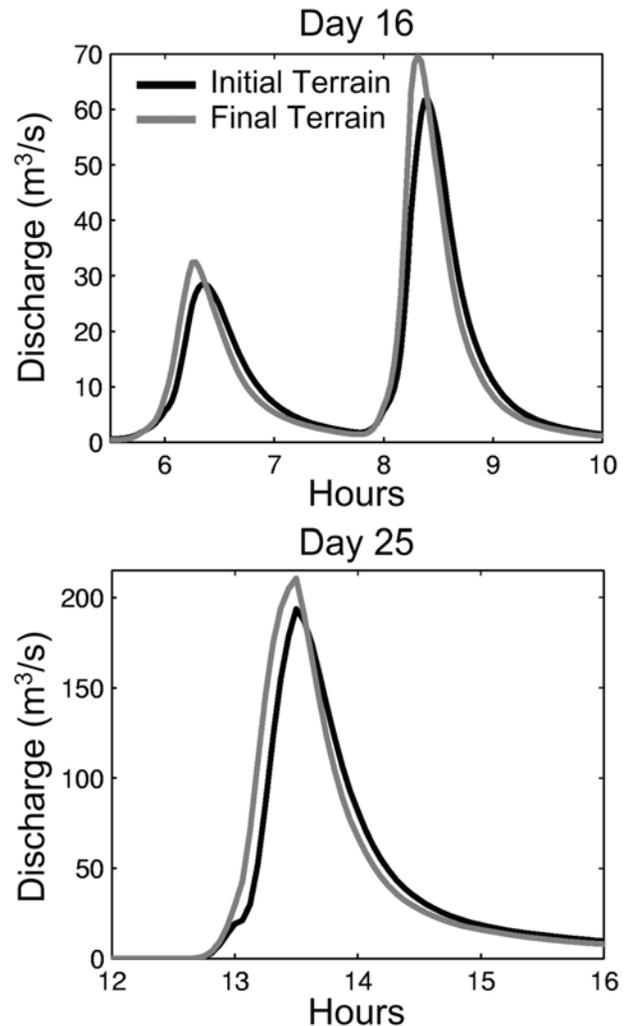

Figure 4. Runoff hydrograph response at the outlet (2.27 km^2) for two selected events (days 16, 25).
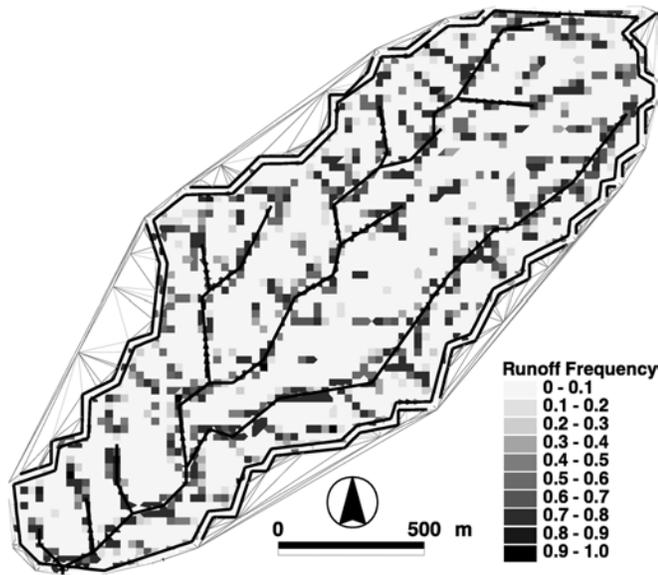
Figure 5. Temporal frequency of infiltration-excess runoff (R_I) for the initial topographic model.
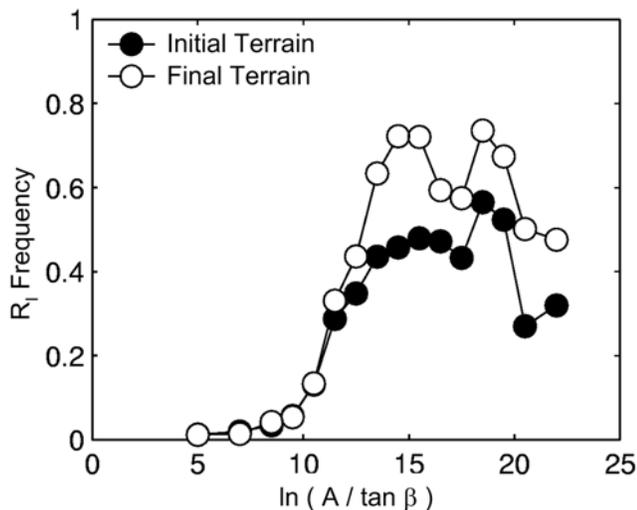

Figure 6. Topographic location of infiltration-excess runoff (R_I) frequency generated over simulation period.

The spatial organization of infiltration-excess runoff is captured in Figure 6 through a topographic analysis of the runoff production regions (Figure 5). Here, we utilize the topographic or wetness index (Beven and Kirkby 1979) to classify basin Voronoi polygons into hydrologically-similar units. The topographic index,

$$\lambda = \ln(A / \tan \beta) \qquad (6)$$

where A is the upslope contributing area and $\tan \beta$ is the surface slope, illustrates the regions preferentially producing infiltration-excess runoff for each

landscape model. Larger values of λ correspond to the flat channel areas, while smaller λ values are attributed to steep hillslope regions. Note that the frequency of runoff production increases between values $\lambda = 12$ to 17 as fluvial erosion shapes the basin geomorphic form. Figure 6 highlights the sharp differences in the runoff response in the basin as erosional processes adjust the landscape to the imposed surface disturbance.

In Figure 7, the effect of fluvial erosion on the surface moisture distribution is investigated for a selected transect in the upper basin reaches. Erosion impacts the elevation profile along the transect, as well as the soil moisture distribution. Note that the initial terrain has a broad channel region with a slightly higher moisture content in the low-lying area. As fluvial erosion incises and deepens the channel in the final terrain, a sharp difference in moisture content is exhibited between the channel and surrounding hillslope regions.
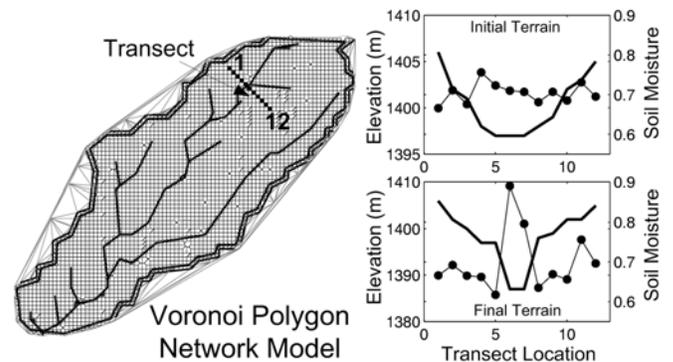

Figure 7. Transect distribution of elevation (solid line) and soil moisture (closed circles).

Conclusions

In this study, we have demonstrated the coupled use of a landscape evolution and a distributed hydrologic model for investigating the impact of fluvial erosion on basin hydrograph and spatial runoff response. Erosion processes are shown to increase the runoff intensity and decrease the response time to rainfall forcing. The application to a Walnut Gulch sub-basin illustrates the capabilities and potential of the proposed integrated framework for understanding the process interaction between basin hydrology and geomorphic form.

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References

Beven, K.J. 1982. On subsurface stormflow: An analysis of response times. Hydrological Sciences Journal 27:505-521.

Beven, K.J., and M.J. Kirkby. 1979. A physically-based variable contributing area model of basin hydrology. Hydrological Sciences Journal 24: 43-69.

Chagnon, F.J.F. 1998. Modeling Daily Rainfall in Walnut Gulch Using Generalised Linear Models. M.S. Thesis, Imperial College, London.

Goodrich, D.C., L.J. Lane, R.M. Shillito, S.N. Miller, K.H. Syed, and D.A. Woolhiser. 1997. Linearity of basin response as a function of scale in a semiarid watershed. Water Resources Research 33(12):2951-2965.

Grayson, R.B., I.D. Moore, and T.A. McMahon. 1992. Physically-based hydrologic modeling. 1. A terrain-based model for investigative purposes. Water Resources Research. 28(10):2639-2658.

Hernández, M., S.N. Miller, D.C. Goodrich, B.F. Goff, W.G. Kepner, C.M. Edmonds, and K.B. Jones. 2000. Modeling runoff response to land cover and rainfall spatial variability in semi-arid watersheds. Environmental Monitoring and Assessment 64: 285-298.

Houser, P., D. Goodrich, and K. Syed. 2000. Runoff, Precipitation and Soil Moisture at Walnut Gulch. In R. Grayson and G. Bloschl, eds., Spatial Patterns in Catchment Hydrology, pp. 125-157. Cambridge University Press, Cambridge, UK.

Istanbulluoglu, E., D.G. Tarboton, R.T. Pack, and C. Luce. 2002. A probabilistic approach for channel initiation. Water Resources Research 38(12):1325.

Istanbulluoglu, E., D.G. Tarboton, R.T. Pack, and C. Luce. 2003. A sediment transport model for incising gullies on steep topography. Water Resources Research 39(4):1103.

Ivanov, V.Y., E.R. Vivoni, R.L. Bras, and D. Entekhabi. Development of a triangulated irregular network model for real-time, continuous hydrologic forecasting. Water Resources Research (in review).

Miller, S.N., D.P. Guertin, and D.C. Goodrich. 1996. Investigation stream channel morphology using a geographic information system. ESRI Conference, Palm Springs, CA.

Nearing, M.A., J.R. Simanton, L.D. Norton, S.J. Bulygin, and J. Stone. 1999. Soil erosion by surface water flow on a stony, semiarid hillslope. Earth Surface Processes and Landforms 24:677-686.

Ogden, F., and A. Heiling. 2001. Two-dimensional Watershed-scale Erosion Modeling with CASC2D. In R.S. Harmon and W. Doe, eds. Landscape Erosion and Evolution Modelling, pp. 272-337. Kluwer Academic/ Plenum Publishers, Dordrecht.

Osterkamp, W.R., and T.J. Toy. 1997. Geomorphic consideration for erosion prediction. Environmental Geology 29(3/4):152-157.

Ritter, J.B., and T.W. Gardner. 1993. Hydrologic evolution of drainage basins disturbed by surface mining, central Pennsylvania. Geological Society America Bulletin 105:101-115.

Schmidt, J., M. Werner, and A. Michael. 1999. Application of the EROSION 3D model to the CATSOP watershed. Catena 37:449-456.

Schumm S.A. 1980. Some implications of the concept of geomorphic thresholds. In D. Coates and J. Vitek, eds., Thresholds in geomorphology, pp. 473-485. Allen and Unwin, London.

Syed, K.H., D.C. Goodrich, D. Myers, and S. Sorooshian. 2003. Spatial characteristics of thunderstorm rainfall fields and their relation to runoff. Journal of Hydrology. 271:1-21.

Tucker, G.E., and R.L. Bras. 1998. Hillslope processes, drainage density, and landscape morphology. Water Resources Research 34: 2751-2764.

Tucker, G.E., S.T. Lancaster, N.M. Gasparini, R.L. Bras, and S.M. Rybarczyk. 2001a. An object-oriented framework for distributed hydrologic and geomorphic modeling using triangulated irregular networks. Computers and Geosciences 27:959-973.

Tucker, G.E., S.T. Lancaster, N.M. Gasparini, and R.L. Bras. 2001b. The Channel-Hillslope Integrated Landscape Development (CHILD) model. In R.S. Harmon and W. Doe, eds., Landscape Erosion and Evolution Modelling, pp. 349-388. Kluwer Academic/ Plenum Publishers, Dordrecht.

Vivoni, E.R., V.Y. Ivanov, R.L. Bras, and D. Entekhabi. 2003. Topography, triangulated irregular networks, and hydrological similarity. Journal of Hydrologic Engineering (in press).

Wolman, M.G., and J.P. Miller. 1960. Magnitude and frequency of forces in geomorphic processes. Journal of Geology 68:54-74.