FEEDBACK MECHANISMS BETWEEN MORPHOLOGY, STORM DURATION AND HYDROGRAPH SHAPES

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ABSTRACT
Relationships between runoff hydrographs discharged from drainage basins shaped by precipitation events of different characteristic duration are analysed. Feedbacks between hydrograph shapes and landscape shaping storm duration are identified: hydrographs resulting in catchments shaped by typically short and intense storms are thinner and peakier for a given precipitation input than hydrographs of catchments in environments of longlasting storms. This finding can be used to extend the well known relationship between catchment planform and hydrograph shape to include the effect of storm duration on hydrograph shape and morphogenesis. The study is based on numerical modelling of landscape evolution and rainfall routing.

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1. INTRODUCTION

Feedback relations between hydrograph shapes and catchment morphology are one of the basic relationships of hydrology and fluvial geomorphology: catchment morphology affects hydrograph shapes, while the topography is eroded by erosion of the runoff hydrograph. This mutual dependency is reflected in the concept of geomorphological unit hydrograph (Rodriguez-Iturbe and Valdez, 1979) and in the early acknowledgment of the effect of catchment shape on peak discharges (Strahler, 1964). The feedback scheme can further be detailed by incorporating storm duration as the third factor, because storm duration affects hydrograph shapes. For short storm durations the shape of the hydrograph is close to the instantaneous unit hydrograph, while for longer precipitation events hydrograph shape approaches a flat, rectangular shape. Hydrograph shapes drive surface erosion, while they are governed by both surface morphology and storm duration.

In an earlier paper (Sólyom and Tucker, 2004) the author has studied the effect of storm duration on landscape evolution and identified compensatory mechanisms between storm duration and hydrograph shapes. It was found that landscapes generated by shorter storms produce peakier hydrographs for the same precipitation event than landscapes generated by long storms. This phenomenon can be interpreted in terms of the energy minimization principle: landscapes strive to minimize their total energy, and this is achieved by maximizing erosion (Rodriguez-Iturbe et al., 1992). For landscapes shaped by dominantly short storms peak discharge is the dominant erosive factor rather than total runoff (Wolman and Miller, 1960), therefore landscapes during their evolution try to maximize peak discharge values. This is achieved by rearranging the flow path structure to produce hydrographs with the highest possible peak discharge values for a given precipitation input. This phenomenon has a number of practical consequences in terms of flood prediction and catchment management. This paper would like to get more explicit about the identified compensatory mechanism by introducing a non-dimensional variable, the hydrograph peakedness factor and studying its evolution in detail.

2. THEORY

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Landscape evolution models simulate the temporal change of the topography. The equations solved numerically on a discretized spatial basis capture the significant hydrological, erosional and tectonic processes (e.g. Howard, 1994; Tucker and Slingerland, 1997). Runoff is often modelled as a linear function of the contributing area corresponding to the rectangular hydrographs of long-lasting storms. To introduce the shape of hydrographs in the model, and to allow for additional feedbacks to develop, hydrograph-related quantities have to be used. Considering that hydrograph duration (Th) separated from the base flow is equal to storm duration (Tr) plus the concentration time (Tt) of the catchment, and that the concentration time can be expressed using longest flow path length (L; the path the water particle has to travel to reach from the most distant location of the catchment to the outlet) and average routing velocity (Uf), one can write:

$$T_h = T_r + \frac{L}{U_f} \qquad (1)$$

Runoff volume in a given catchment after a storm event ($(R-I)AT_r$) can be equated with the corresponding hydrograph volume ($T_h Q_p F_{hs}$) and solved for peak discharge using (1):

$$Q_p = \frac{(R-I)A}{F_{hs}} \frac{T_r}{T_r + L/U_f} \qquad (2)$$

- where R is time- and space-averaged rainfall intesity, *I* is time- and space-averaged infiltration rate ($I<R$), *A* is contributing area, Q_p is peak discharge, F_{hs} is hydrograph shape factor giving the ratio of the hydrograph within the T_h, Q_p rectangle, it takes values between 0 and 1, e.g. 0.5 for triangles.

Erosion exerted by running water can be related to shear stress expressed as a power function of hydrograph flow depth (Q(t)) and local slope (S) (Whipple and Tucker, 1999). Considering that a flood hydrograph Q(t) can be nondimensionalized by scaling with peak discharge Q_p, and time t with T_h respectively, the storm-averaged erosion rate E can be given as:

$$E = \frac{1}{T_h}\int_0^{T_h} K[Q(t)]^m S^n dt = K{Q_p}^m S^n \int_0^1 Q`(t`)^m dt` =$$

$$\frac{K(R-I)^m A^m S^n F_{he}}{{F_{hs}}^m} \frac{{T_r}^m}{(T_r + L/U_f)^m} \qquad (3)$$

- where K is erosion coefficient, S is slope, Q’ and t’ are nondimensional hydrograph and time respectively, F_{he} is the integral of $Q'(t')^m$, m and n are positive constants usually between 0 and 2. Both F_{he} and F_{hs} take values in the range of 0 to 1.

For long storms ($T_r >> L/U_f$) $F_{he} \sim F_{hs} \sim 1$ and equation (3) simplifies to $E=K(R-I)^m A^m S^n$, which is the standard erosion equation for steady and uniform runoff. For short storms, however, equation (3) becomes sensitive to both the storm duration-travel time relationship and to the contributing area-flow path length relationship. This latter relates to the planshape of the catchment and guarantees higher peak discharge and erosion values for round catchments than for elongated ones.

3. NUMERICAL SIMULATIONS

Using equation (3) simulations have been performed and dynamic equilibrium landscapes produced for long-storm and for short-storm conditions. The simulations were detachment limited (Howard, 1994) in the sense that eroded material was removed immediately and not cascaded downslope as in the case of the transport limited erosional system. This approach mimics the characteristic of arid landscapes that thin soil is easily removed by erosion, and transport capacity generally exceeds detachment capacity. Dynamic equilibrium has been reached when denudation at every point on the surface has counterbalanced the rate of the spatially constant uplift rate (Hack, 1960). The simulation domain was an initially flat 40*40 raster with an additional random noise to facilitate network formation.

Two dynamic equilibrium topographies were simulated, one with long storms ($T_r >> L/U_f$) and one with markedly short storms: the $T_r/(T_r+L/U_f)$ fraction at simulation window-length was 1/40. In order to compensate for the total precipitation decreasing effect of decreasing storm duration, rainfall rate (R) for the short storm case has been increased to generate identical total precipitation (T_r*R) in both cases. In this way the tectonic uplift rate has been counterbalanced by the same amount of time-integrated precipitation fallen, only the duration and intensity of the modelled events were different: higher intensity for the short-storm case, and gentle intensity for the long-storm case. In the short-storm case F_{he} and F_{hs} were given the typical value of 0.4. As it will be demonstrated later at low storm duration F_{hs} takes values in a relatively stable range, so that using the fixed value of 0.4 does not introduce considerable amount of bias into the calculations.

Figures 1a and 1b present the two surfaces. The long-storm surface shows a sinuous channel network pattern, whereas the short storm surface is characterised by straight channel segments. The surfaces presented in Figures 1 and 2 represent end-member-cases on a continuous scale. Differences in landscapes shaped by storms of different duration can be less pronounced than in this rather demonstrative case. It is also acknowledged that changes in storm duration and rainfall intensity can have simultaneously a number of different outcomes as well, such as changes in the vegetation cover or in the grain size distribution, but here we remain focused on the consequences of the changing storm duration.

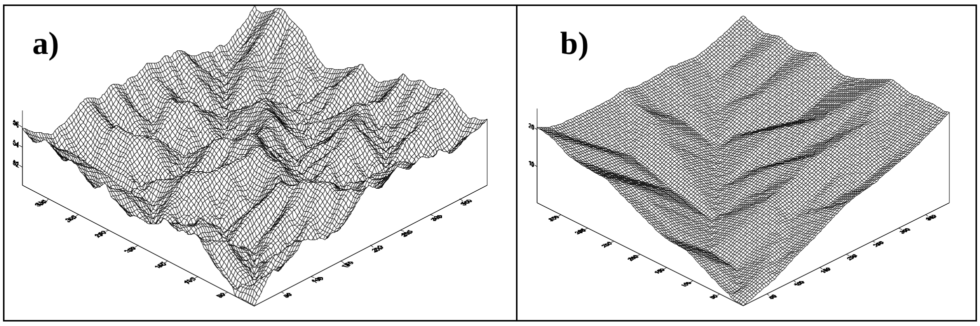

Fig. 1. ***Simulated dynamic equilibrium surfaces. In the case of surface a) storms were infinitely long, while surface b) has been simulated with storm durations markedly shorter than the concentration time of the basin. One corner outflow has been applied, and both runoff (m) and slope (n) exponents were set to unity.***

In order to analyse the flood wave producing characteristics of the two surfaces a rainfall-runoff simulator with constant runoff velocity has been used. A series of storm events with increasing duration was simulated and hydrograph metrics were recorded at the outlet. The hydrograph metrics recorded for each flood event were: peak discharge, the hydrograph shape factor (F_{hs}) relating the area under the hydrograph curve to the peak discharge-hydrograph duration window, and the hydrograph peakedness factor (F_{hp}) comparing peak discharge to the square root of hydrograph volume:

$$F_{hp} = \frac{Q_p}{\sqrt{Q_p T_h F_{hs}}} . \tag{4}$$

Substituting Q_p with (2) and using travel time, T_t, (identical to concentration time) instead of L/U_f:

$$F_{hp} = \frac{(R-I)^{0.5} A^{0.5}}{F_{hs}} \frac{T_r^{\ 0.5}}{T_r + T_t} . \tag{5}$$

For short storms ($T_r \ll T_t$) (5) reduces to $F_{hp} \sim Tr^{0.5}$, while for long storms ($T_r \gg T_t$) $F_{hp} \sim Tr^{-0.5}$. According to this hydrograph peakedness increases with increasing storm duration when storms are short, while it decreases when storms are long. The physical explanation for increasing peakedness at low storm durations is that runoff volume increases linearly with storm duration but hydrograph duration increases only less than linearly. The cause for decreasing peakedness at long storms is that peak discharge stops growing as soon as storm duration equals the concentration time while hydrograph duration still increases. This general picture, however, is somewhat modified by the changing value of F_{hs} for it increases slowly from low values (~0.4) towards unity, but this effect does not change the general trend of the peakedness dynamics.

To answer the question when the hydrograph peakedness factor reaches its maximum equation (5) can be differentiated with respect to storm duration and solved for 0. Given that no analytical expression between F_{hs} and T_r is known and that F_{hs} changes only slightly for $T_r < T_t$, F_{hs} has been considered as an independent constant in the differentiation. For constant F_{hs} F_{hp} reaches maximum when $T_r = T_t$. Hydrographs are the peakiest or in other words they are most effective in transforming runoff volume into peak discharge when storm duration is equal to or comparable to the concentration time of a catchment.

4. RESULTS AND CONCLUSIONS

Figures 2-4 show the hydrograph metrics of the rainfall-runoff simulations. For both surfaces peak discharge values grow with increasing storm duration until they reach maximum, in this case 1600 units, corresponding to the area of the simulation field times rainfall intensity. For the long-storm surface (SL) maximum runoff is reached at around storm duration 100, for the short-storm surface (SS) already at around storm duration 50. This is due to the considerably shorter concentration time in the second case. Additionally to this there is a difference in the style of the growth rate of peak discharge with increasing storm duration. In the case of SL peak discharge grows close-to-linearly, while for SS the peak discharge curve is upward convex. This is due to differences in the drainage area organisation between the two surfaces: SS is characterized by stronger flow path convergence than SL. At low storm durations, which correspond to the genetic storm duration of the topography, SS is more sensitive in terms of hydrograph peak flow to changes in storm duration than SL.

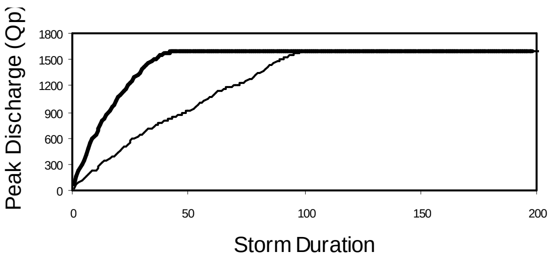

Fig. 2. ***Peak discharge rates at the outlet of the simulated topographies for storms of different duration. Thin line stands for the long-storm surface, thick line for the short-storm surface.***

The changes in the hydrograph shape factor F_{hs} are less for storm durations below the concentration time, than for storm durations exceeding it (Fig. 3). In this latter case F_{hs} grows steadily towards 1. For storm durations below concentration time SS shows lower F_{hs} values (<0.4) than SL (>0.4) indicating thinner hydrographs due to different flow path organisation.

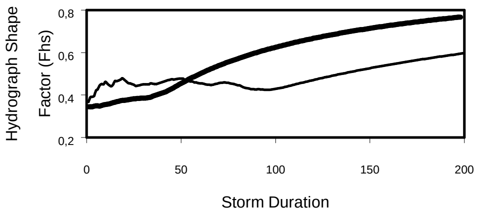

Fig. 3. ***Hydrograph shape factor at the outlet of the simulated topographies for storms of different duration. Thin line stands for the long-storm surface, thick line for the short-storm surface.***

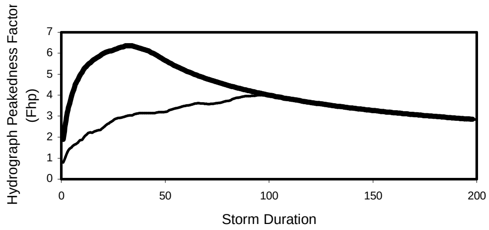

Fig. 4. ***Hydrograph peakedness factor at the outlet of the simulated topographies for storms of different duration. Again, thin line stands for the long-storm surface, thick line for the short-storm surface.***

The hydrograph peakedness factor (F_{hp}) shows the dynamics outlined in the discussion of equation (5). For low storm duration it relates to the square root of storm duration, for higher storm duration to the inverse of the square root of storm duration. In addition to this there is a good agreement with F_{hs} dynamics accounting for small-scale patterns in the F_{hp} curve. In general SS shows higher F_{hp} values due to lower basin concentration time and thinner hydrographs (lower F_{hs}).

The results outlined above point to the fact that surfaces created by short and intense precipitation generate hydrographs that are more peaked in shape and also higher than the hydrographs of the same precipitation in basins originally shaped by long-lasting storms. This is due to the different morphology responsible for differences in concentration time and in drainage area organisation. One way to interpret this phenomenon is to consider it as an outcome of landscape self-organisation. According to equation (3) storm-averaged erosion rates, in environments where the typical duration of storms is less than basin concentration time, relate more to peak discharge than to total runoff. Erosion rates in these environments can be maximized, and hence total energy minimized by maximizing peak discharges of flood hydrographs. This is achieved by reorganizing the landscape through the work of erosion to decrease flow path length and increase the area-length ratio and flow convergence at key locations.

The more practical consequences of this study concern scenarios of climate change. Climate change in Central-Europe is likely to increase the probability of high magnitude precipitation events, basically that of intense and short-storms. The consequences in terms of flood prevention are obvious, more intense storms result higher flood waves. Less obvious is the fact that landscape evolution will additionally boost the generation of severe flash floods by shifting landscape morphology towards surfaces typical of short-storm environments. This means that hydrographs will get peakier (F_{hp}) and thinner (F_{hs}) for a given storm event than they were before, and that the sensitivity of peak discharge values to changes in storm duration will increase producing higher peak discharge increments for a given climate shift than before. The hydrological consequences of climate change are immediate, but most of the geomorphological changes take place only on a longer timescale.

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