

Knickpoints and hillslope failures: Interactions in a steady-state experimental landscape

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ABSTRACT

Hillslope stability depends strongly on local conditions, such as lithology and rock strength, degree of saturation, and critical slope angle. Common triggers for slope failure include severe storms, earthquakes, and removal of material from the toe of the hillslope. In this paper, we focus on the latter, in a model in which streams incise the toe and destabilize the hillslope. We investigate possible interactions between migrating knickpoints and hillslope failures in a small-scale, steadily eroding experimental landscape that experiences steady rainfall and base-level fall conditions. We monitored knickpoint propagation and hillslope failure activity with time lapse photography over a time period in which numerous knickpoints migrated through the drainage basin. We then investigated temporal and spatial relationships between hillslope failures and knickpoints and compared these results to Monte Carlo simulations of hillslope failure distributions. When focusing along a single channel, we found that, statistically (significant at the 98% confidence level), a greater number of failures occur downstream from a migrating knickpoint. These results highlight both the organized and random nature of hillslope and knickpoint interactions.

Keywords: knickpoints, landslide triggering, evolution, hillslope failure.

INTRODUCTION

Landslides have a profound impact on societal structures and cause billions of dollars of damage in the United States alone each year (Schuster and Highland, 2001). They also play a significant role in denudational processes in eroding drainage basins.

Hence, there is significant motivation to understand the controls of landslide initiation, as well as the timing, location, and size of landslides. In this paper, we study stream and hillslope interactions in a controlled experimental drainage basin. We test the hypothesis that stream incision driven by migrating knickpoints can impose a spatial and temporal pattern on landslide

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distributions. Before we begin our analysis, we provide a brief overview of landslide studies.

Local controls on landsliding involve several important variables, including lithologic structure, soil development and structure, pore fluid pressure, topographic setting, and vegetative cover. A Mohr-Coulomb relation between stress and failure (Terzaghi et al., 1996) forms the basis for estimating the critical stress at which a hillslope will fail. There are several ways for the motion threshold to be exceeded. Common triggers include severe rain storms, where increased pore fluid pressure facilitates failure (Selby, 1982; Burton et al., 1998; Dietrich et al., 1995; Iverson, 2000), earthquakes, where ground shaking induces failure (Keefer, 1994; Harp and Jibson, 1995; Crozier et al., 1995; Havenith et al., 2003), and removal of material and support from the toe of the hillslope (Schumm, 1956; Densmore et al., 1997; Larsen and Parks, 1997). We investigate this last mechanism in our study. Vegetation exerts control on substrate resistance, and this adds further complexity to the susceptibility of hillslope failure (Sidle, 1992; Duan, 1996; Montgomery et al., 2000; Gabet and Dunne, 2002).

Spatial and temporal distributions provide an estimate of the contribution of landsliding to the erosional budget for landscapes, and offer probabilistic tools for predicting landslide events in a given area (van Asch and van Steijn, 1991; Hovius et al., 1997; Larsen and Torres-Sanchez, 1998; Miller and Sias, 1998; Hermanns et al., 2000; Densmore and Hovius, 2000; Trauth et al., 2000; Stark and Hovius, 2001; Guzzetti et al., 2002; Martin et al., 2002; Dadson et al., 2003; Brardinoni and Church, 2004). Increasingly, physics-based modeling has coupled topographic and weather information with stability criteria, and this approach offers predictions for the location and timing of landsliding (Iida, 1984; Casadei et al., 2003). Landslide size-frequency studies have also employed physical experiments (Densmore et al., 1997) in which a simulated granular hillslope composed of beans responded to base-level fall.

Due to the local conditions that control hillslope stability, one might expect that landslide occurrences are stochastic in time and space (e.g., Benda and Dunne, 1997). Some spatial patterning results from the origination of shallow landslides in hollows in low-order drainages (Campbell, 1975; Montgomery and Dietrich, 1994; Benda and Dunne, 1997). In this case, the spatial pattern is governed by drainage basin structure. Temporal patterns of landslides are largely related to triggering by storm or earthquake events. However, time series of shallow landslides generated from experimental (Densmore et al., 1997) and physics-based models (Benda and Dunne, 1997) are highly stochastic, emphasizing the sensitivity to local conditions.

We now turn to an additional means of destabilizing hillslopes in natural settings: removal of material from the toe of the hillslope by streams. This mechanism has received less attention, largely due to the longer time scales involved in stream incision. While bedrock incision by streams involves a variety of mechanisms (Wohl, 2003; Hancock et al., 2003; Sklar and Dietrich, 2003), we focus on two styles of stream incision in this paper:

a steady profile lowering due to uniform erosion of the bed, and knickpoint migration.

Knickpoints can play a significant role in river incision and valley development (Ahnert, 1998). Knickpoints are step changes in bed surface elevation where intense, localized erosion takes place (Brush and Wolman, 1960; Gardner, 1983; Bennett et al., 2000). Formation of knickpoints and their upstream migration have been linked to concentration of overland flow (Mosley, 1974; Merritt, 1984), and rill and gully erosion (Bryan, 1990; Slattery and Bryan, 1992). They are an important erosional process in bedrock channels (Miller, 1991), and landscape evolution (Dietrich and Dunne, 1993; Zaprowski et al., 2001). The mechanism of upstream knickpoint migration has been the object of several experimental, theoretical, and field studies (Brush and Wolman, 1960; Holland and Pickup, 1976; Gardner, 1983; Bryan and Rockwell, 1998; Bennett et al., 2000; Parker and Izumi, 2000; Alonso et al., 2002; Crosby and Whipple, 2002), where the effects of varying bed material, water table height, slope, and flow discharge on migration rate have been explored.

While numerous studies of hillslope stability, river incision, and knickpoint behavior have been conducted, these studies have not looked into a systematic relationship between knickpoint propagation and hillslope failure activity. There are good reasons for this omission. Knickpoints in bedrock channels require a significant amount of time to propagate up through a drainage basin, and so field studies of stream incision and hillslope response are limited by the length of time required to observe this kind of behavior in natural landscapes. Hillslope adjustment to a lowering river bed via landsliding has been documented as a significant response by Burbank et al. (1996) in the northwestern Himalaya, but the connection between stream incision and knickpoint propagation is not known for this case.

We pursue the effect of stream incision on hillslope stability in this paper by postulating that hillslope failures should exhibit spatial and temporal patterns controlled by knickpoint propagation. Namely, if a stream is actively downcutting at the toe of the hillslope, and stream incision is due to the migration of a knickpoint, then hillslope failures will follow in the wake of the knickpoint. According to this assumption, knickpoint location and migration should have an influence on the spatial and temporal patterns of landslides. A small experimental drainage basin provides a convenient setting to test the strength of coupling between stream incision and hillslope failures. Recent research (Hasbargen and Paola 2000, 2003; Lague et al., 2003) has demonstrated the utility of monitoring experimental eroding landscapes under steady uplift and rainfall conditions. These experiments have documented hillslope failures and knickpoints as common erosional processes within laboratory drainage basins (Hasbargen, 2003). Hence, basic interactions between stream incision and failures can be studied in a controlled environment, and they provide a suitable setting to test the idea that knickpoints impose a spatial and temporal pattern of failures in their wake. As a side note, hillslope failures come in a variety of sizes and styles of movement. While we recognize the diverse charac-

ter of mass movements on hillslopes in natural settings, we will use the terms “hillslope failure” and “landslide” interchangeably throughout this paper. Because weathering and soil development are absent in our experimental landscape, shallow landslides of soil are absent in our experiment. Landslides in our erosional facility are analogous to deep-seated bedrock landslides.

DESCRIPTION OF THE EXPERIMENTAL APPARATUS

A small-scale physical experimental apparatus was set up at St. Anthony Falls Laboratory of the University of Minnesota (Hasbargen and Paola, 2000; Hasbargen, 2003). The apparatus consisted of a nearly circular steel tank ~ 1 m in diameter and 1 m deep with a single outlet dammed by a motor-controlled gate (Fig. 1). The outlet was 1 cm wide. A motor was attached to the sliding gate via a cable. We ran the motor continuously during the experiment, dropping the outlet at a slow, constant rate. The effect of dropping base level is equivalent to uniform block uplift of the basin relative to base level. We took numerous measurements of the outlet height during the experiment to verify steady base-level fall. A set of 8 greenhouse misters placed 70 cm above the upper level of the tank sprinkled rain (droplet size $<200 \mu\text{m}$)

over the basin, generating runoff. A pressure regulator maintained a constant pressure to the mist apparatus.

The general behavior of this experimental system under variety of conditions has been reported in Hasbargen and Paola (2000, 2003). For the present study, we carried out detailed measurements of landslide distribution and knickpoint migration in one experiment. The experimental conditions were: rainfall rate = $10.83 \mu\text{m/s}$, base-level fall rate = $3.1 \mu\text{m/s}$. Before beginning the experiment, we calibrated the rainfall spatial distribution by collecting rainfall in pans at the top of the basin. The spatial coefficient of variation was $<15\%$ over a measurement interval of 12 min ($n = 27$). At the beginning of the experiment, the basin was filled with erodible material consisting of a well-sorted silica silt ($D_{50} = 45 \mu\text{m}$) mixed with kaolinite (1% by weight). These were mixed with water to the consistency of a medium cement in a cement mixer, poured into the basin, and allowed to settle overnight.

After preliminary calibration of rainfall and base-level fall rate, we initiated the experiment by turning on the motor-controlled outlet and rainfall. The run lasted for 63 h, at which time the sliding gate outlet reached the bottom of the basin. Initially, the surface was flat, and runoff patterns were essentially random (Fig. 2). Upon complete dissection of the initial surface, a 3–5 order drainage network had developed (Fig. 3). The dissection of the initial flat surface required ~ 15 h. Digital stereo-images (1280×960 pixel resolution) of the basin were collected at 7–10 min intervals. Time-lapse video recorded snapshots every 100 s. Sediment flux at the basin outlet was measured by weighing sediment and water in a handheld graduated cylinder, and recording the time required to fill it. We episodically applied a thin veil of colored sand over the surface as a tool for the identification of topographic features, such as terraces (Fig. 4) and hillslope failures (Fig. 5). The erosion of the colored sand provided an indication of both the length of time required to erode the surface, and a visual record of spatially variable erosion.

We collected 330 photographs, of which 96 were selected for mapping the position of knickpoints and the location and size of hillslope failures. These 96 photographs covered the last part of the experiment, an interval of 13 h, during which time the landscape eroded at a flux steady-state condition (Willett and Brandon, 2002), an amount of time sufficient for the landscape to erode through 14 cm of the substrate, or ~ 1 unit of local relief (11 cm).

EXPERIMENTAL RESULTS

Qualitative Observations of Drainage Basin Dynamics

Despite temporally steady external forcing and flux steady-state conditions, the drainage network exhibited interesting non-steady dynamic behavior, as in the experiments reported in Hasbargen and Paola (2000, 2003). We noted short-term processes, such as hillslope failures and runoff-based erosion; intermediate time-scale processes, such as knickpoint development and

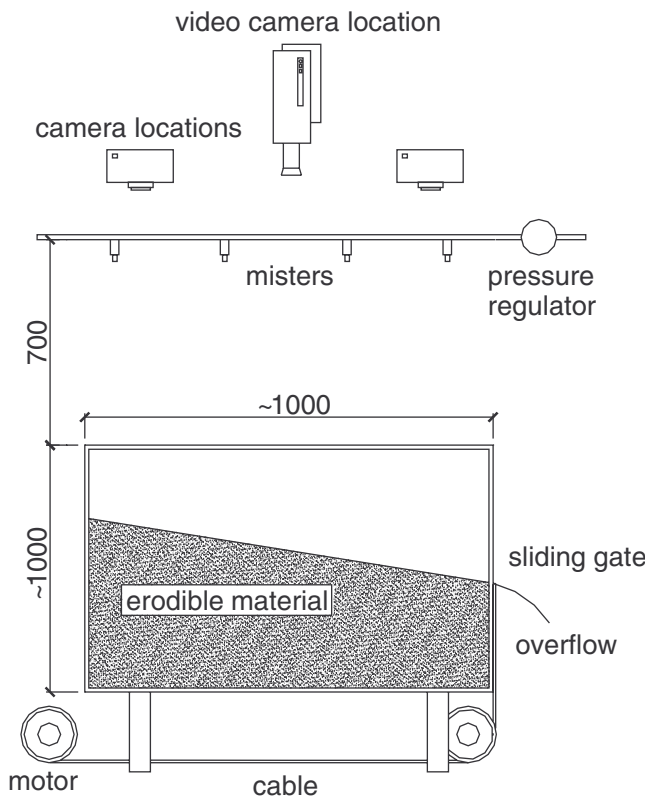


Figure 1. Schematic cross section of the experimental erosion facility. A steel cable drops the outlet; it is wrapped on a pulley and driven by an electric motor mounted on the floor. Dimensions are in millimeters.

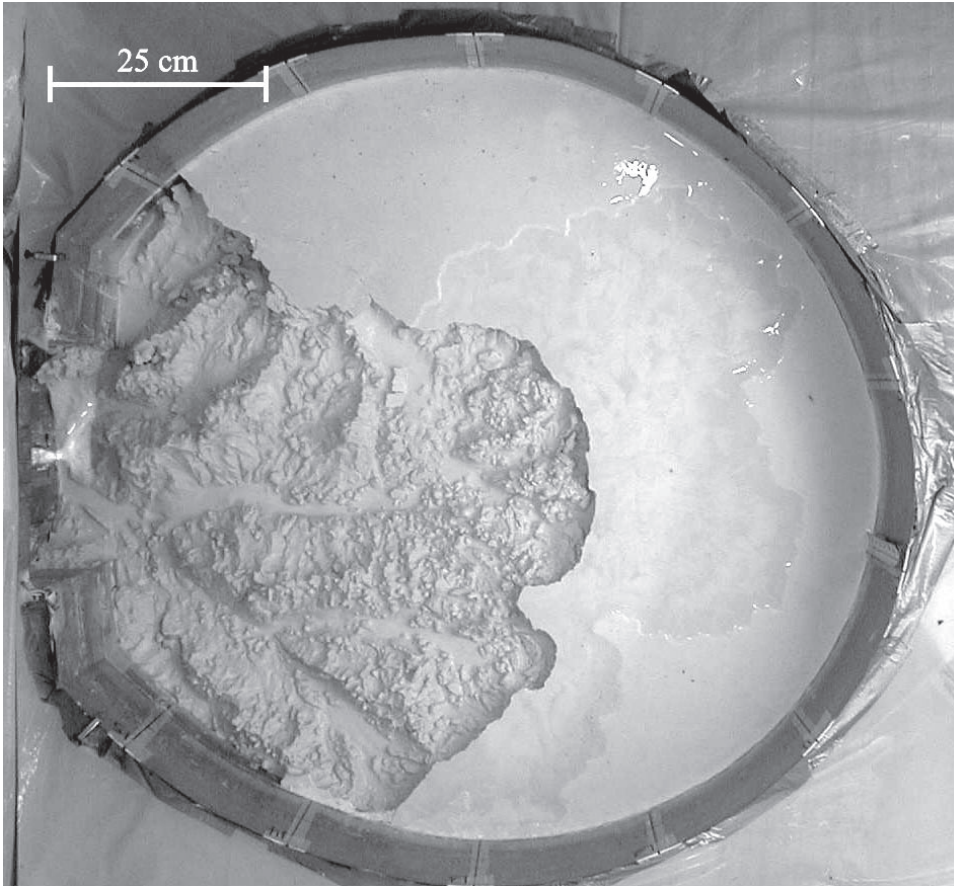


Figure 2. Vertical view of the experimental basin at the beginning of the run during dissection of the initial flat surface.



Figure 3. Vertical view of the dendritic pattern of the drainage network. The photo was taken long after complete dissection of the initial surface (note rind near the top of the basin walls) at run time 62:13 h. Outlet is at left center. Basin length (left to right) is 98 cm; basin width (top to bottom) is 86 cm.

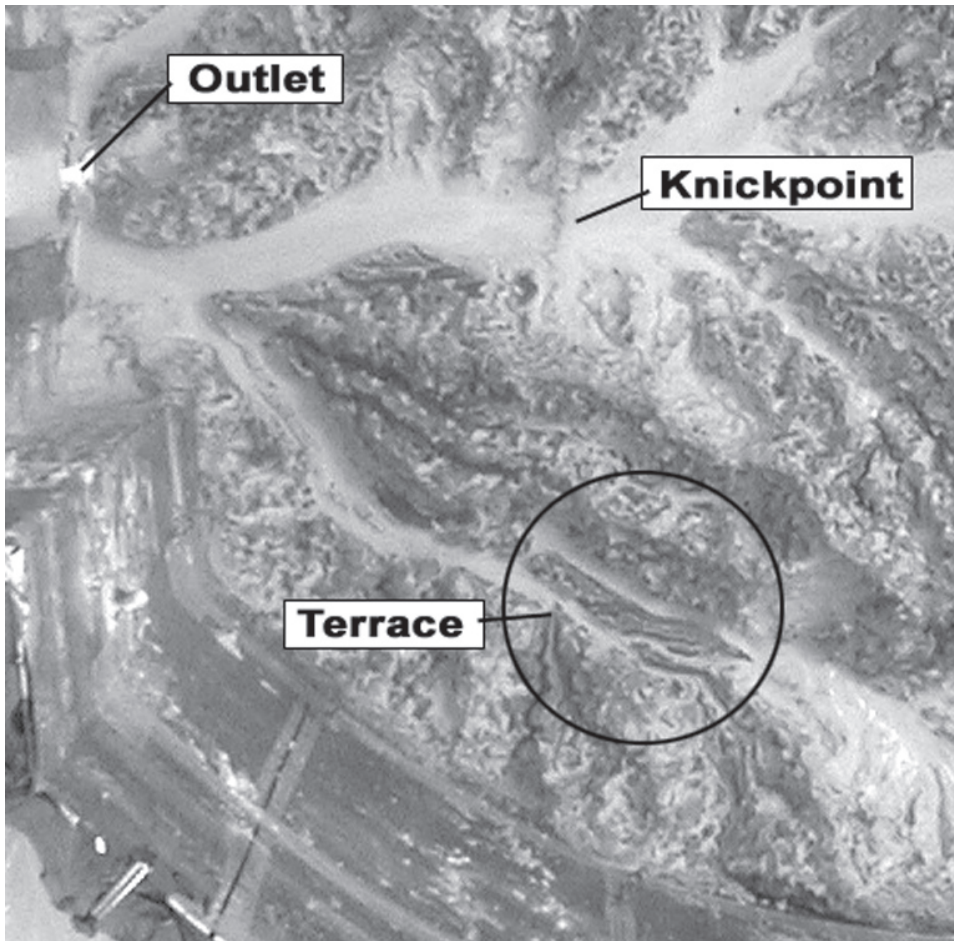


Figure 4. Image of the experimental basin showing wide valley of trunk stream, diagnostic of temporary sediment storage; knickpoint incising into trunk stream; and island and terrace-like structures in the tributary channel in the lower portion of image.

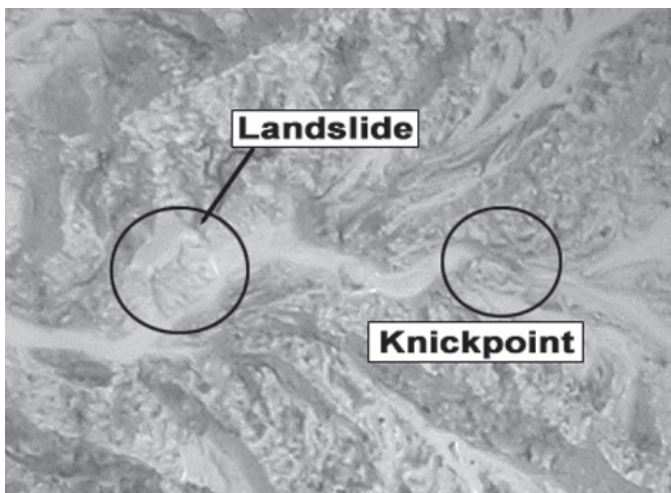


Figure 5. Close-up view of a hillslope failure in the trunk stream after the passage of a knickpoint. Approximate width of image is ~25 cm.

migration, and temporary sediment storage in trunk valleys; and long-term behavior marked by lateral ridge crest movements. Runoff-based erosion was the dominant mechanism for removing material from the basin; it was also the most difficult to detect visually, because flows were rarely more than a few mm deep. We observed knickpoints that typically initiated in the lower reaches of the basin and propagated upstream, apparently triggering hillslope failures.

Rainfall was necessarily stopped before collecting photographs. We took advantage of these occasions to determine how long surface runoff persisted after cessation of rainfall. Flow at the outlet approached nil within a few seconds, implying rapid draining of groundwater from hillslopes and/or very low transmissivity of groundwater in the substrate. Overall, we could not detect obvious effects on landscape development from rainfall cessation and recommencement. Hillslope failures were easier to detect than surface runoff erosion and appeared as abrupt shifts in ridge crest location and as concave hillslopes with a slump at the hillslope toe (Fig. 5).

Episodic cycling between temporary sediment storage in trunk streams and excavation of stored sediment by knickpoints marked the evolution of the landscape throughout the entire

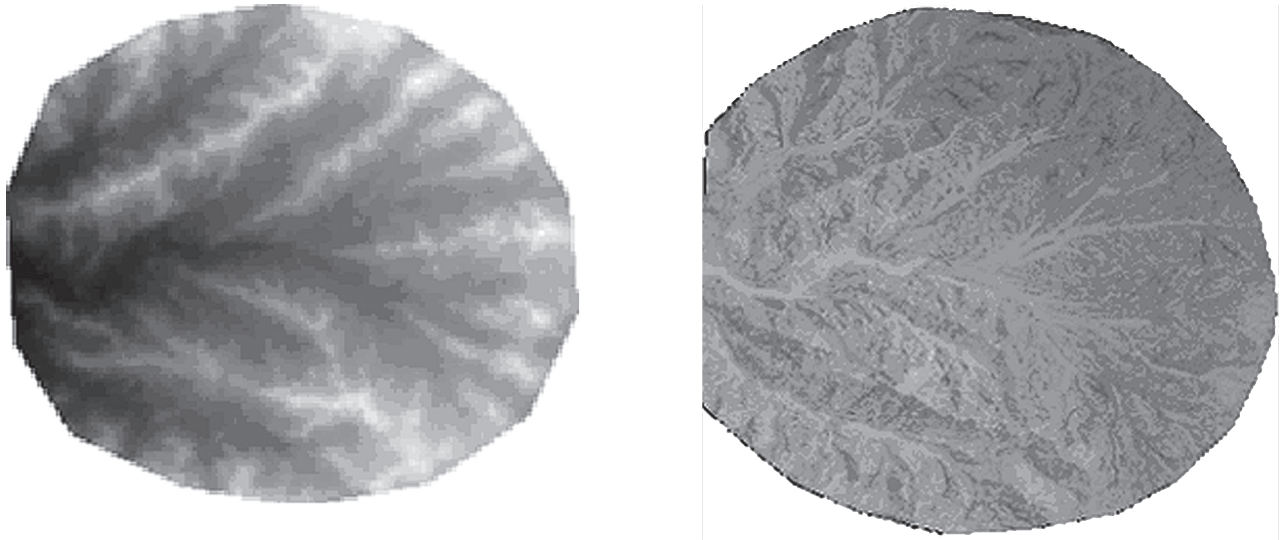


Figure 6. Grayscale digital elevation map (DEM) with pits removed (left), and vertical photograph (right, July 18, photo 17, run time 54:16 h). Long dimension of each image is 90 cm, and width is 86 cm. Grid spacing for DEM is 0.5 cm. Total relief is 22 cm; local relief is 11 cm.

experiment. During times of temporary sediment storage, trunk streams exhibited wide, smooth valley floors with no clearly defined channel. Sediment storage occupied up to 15% of the basin surface area at any one time. Depositional episodes ended when a knickpoint initiated and migrated upstream. Streams deepened and narrowed and rapidly flushed out stored sediment. Similar types of behavior have been noted for experimental channels following an abrupt base-level drop (Cantelli et al., 2004). After the passage of the knickpoint, sediment storage began again, and the sequence was repeated. In some cases, a smooth valley floor developed more than one channel as a knickpoint propagated upstream. Some channels developed marked sinuosity, though most reaches were straight. We did not observe braided channels, though around knickpoints some islands developed. The time scale for a cut and fill cycle ranged from 1 to 1.5 h, equivalent to 1.1–1.7 cm of base-level fall. When this fall distance is scaled to the typical knickpoint height, the cut/fill cycle time is equivalent to the time needed for ~ 2 knickpoint heights of erosion.

Measurements of Hillslope Failure, Knickpoint, and Temporary Sediment Storage Area

We offer the following measures to give an approximate scale of our experimental landscape, and to facilitate comparison to natural drainage basins. We extracted a few digital elevation models (DEMs) from stereo photographic snapshots of the basin during the course of the experiment to provide basic topographic information (see Fig. 6). Maximum relief was 24 cm in our experiments, with local ridge-to-valley relief of 10–12 cm. Maximum relief divided by basin length (98 cm) yielded a regional slope value of 0.24. Mean steepest descent slope computed at 5 mm grid spacing was 0.90. Hillslope lengths (distance from divide to channel) ranged from 1 to 10 cm. Low-order channel widths

were 0.1–0.2 cm, and trunk valley widths during times of sediment storage ranged up to 5 cm. Upon dissection by a knickpoint, channel widths of trunk streams decreased to ~ 1 cm. Experimental hillslope failures commonly extended from ridge crest to valley floor, and ranged in size from 1 to 50 cm². As noted earlier, shallow landslides associated with soil development were absent in the experimental basin. The hillslope failures in our experiment are more appropriately thought of as deep-seated landslides. We present topographic profiles of a few failures and a lower-order channel in Figures 7 and 8. Relief of most knickpoints was ~ 0.5 cm, or 5% of the local ridge-to-valley relief. However, some

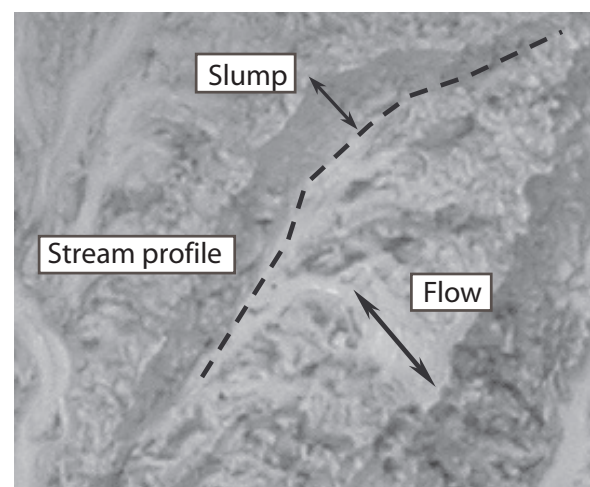


Figure 7. Vertical photograph of two mass movements on hillslopes, showing the location of slump, flow, and stream profile for which topographic profiles were extracted from a digital elevation model (run time, h:min = 54:16).

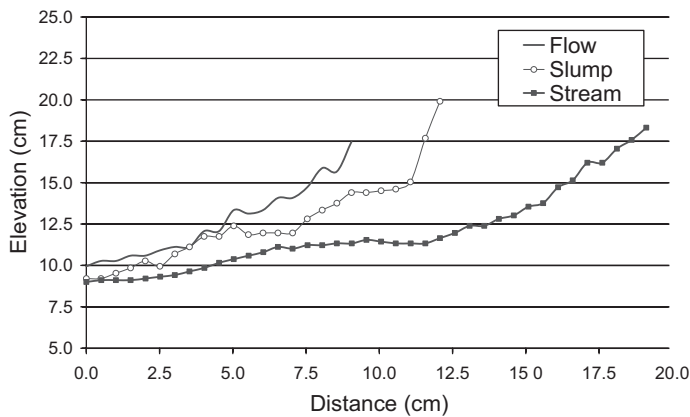


Figure 8. Example of hillslope and channel profiles in the experimental landscape depicted on Figure 7. The feature designated flow appears to be a mass flow, and the feature designated slump exhibits signs of a scarp and irregular deposit at the toe of the hillslope. A stream profile for a second-order channel is plotted to provide a lower limit for relief.

knickpoints exhibited heights of 1–2 cm (10%–20% of local relief). Flat surfaces resembling terraces were noted during this experiment (Fig. 4). They were small, with surface area of 10–20 cm². They typically persisted for relatively long times (about 1 h on average, which was the time required to erode through ~1 cm, or 10% of local relief in the basin). Interestingly, all of these features, when scaled to appropriate vertical and horizontal length scales, such as the hillslope length and local relief, are of the same order as natural mountainous landscapes.

In order to analyze the spatial distribution of hillslope failures, we examined a total of 96 images taken during the last 13 h of the experiment. During this period, base level fell 14 cm, a distance roughly 50% of the total relief of basin. We mapped 505 hillslope failures, and we noticed that the landslide trace remained visible for about two minutes after collapse. Since the time step between photographs was about seven minutes, it is likely that not all of the hillslope failures that occurred between photographic snapshots were mapped.

The surface area and centroid location of each landslide were manually determined on scaled photographs using the image processing software Scion Image. Table 1 reports statistics computed on the mapped failures. The hillslope failures we detected had a mean area of 11.1 cm² and a standard deviation of 9.7 cm². The smallest recorded failure had an area of 1.4 cm²; the largest had an area of 62 cm². Smaller events were more numerous than large ones. The size-frequency distribution of landslides can be approximated by a power law with decreasing numbers of larger events (Fig. 9). This result is comparable to those of studies of hillslope failures in natural settings (e.g., Hovius, et al. 1997; Stark and Hovius, 2001; Guzzetti et al., 2002; Brardinoni and Church, 2004), although ideally a much larger number of events over a broader size range would better define such a relation.

TABLE 1. MAIN CHARACTERISTICS OF THE EXPERIMENTAL RUN

Study interval	13 h
Rainfall rate	10.8 $\mu\text{m/s}$
Base-level fall rate	3.1 $\mu\text{m/s}$
Average time step between photographs	7 min
Number of photographs evaluated	96
Number of hillslope failures mapped	505
Smallest failure detected	1.4 cm ²
Largest failure detected	62.8 cm ²
Mean failure area	11.1 cm ²
Basin area	6400 cm ²

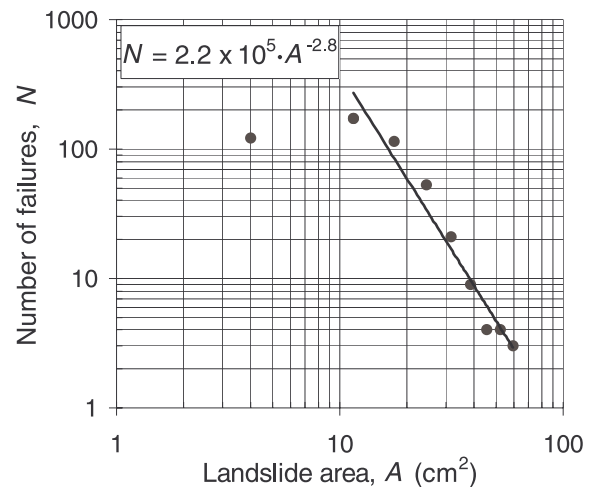


Figure 9. Frequency distribution of hillslope failures during a 13 h period under steady erosion conditions. Typical of landslide distributions in natural settings, the distribution exhibits power-law scaling, though the range in failure size is smaller than for natural settings. The power law on the diagram yields the number of failures (N) of a given area (A). Decreasing numbers of small events could result from difficulty in detection, or represent a lower limit to mass movement size.

We also measured knickpoint locations from the same set of photographs. Three major knickpoint events initiated within 20 cm of the outlet and propagated throughout the basin. Nine other knickpoints initiated 20–50 cm from the outlet. Of these, some propagated to the edges of the basin, while others dissipated. Such behavior has been observed in other studies (Parker, 1977; Hancock, 1997). Migration speed for knickpoints in trunk streams was ~0.6 cm/min; in the upper part of the experimental basin, we measured decreased velocities (~0.4 cm/min) as the knickpoint migrated into smaller tributaries.

Spatial Patterns and Relationships Between Hillslope Failures, Knickpoints, and Temporary Sediment Storage

The main purpose of this study was to identify and characterize the possible presence of patterns in the spatial distribution of landslides, and determine what, if any, relationship exists

between landslides and knickpoints. Before we search for relationships between processes, it is helpful to know if any pattern is detectable in the spatial distribution of hillslope failures. Hence, a null hypothesis might be that hillslope failures are randomly distributed in space across the landscape. To test this hypothesis, we applied a Monte Carlo simulation technique (Metropolis, 1987). We numerically generated 100 sets of 505 randomly located landslides over the experimental basin, so that observed and synthetic hillslope failures were equal in number. We then analyzed the clustering tendency in experimental and random distributions of landslides. A qualitative visual inspection of failure locations for a 4 h period mapped onto a single image (Fig. 10) suggests that some clustering exists in the experimental data.

Clustering tendency was determined by measuring for each failure, i , the distance w_i to the closest landslide j , for both randomly distributed and experimental data sets. We indicate the distance between the centroids of landslide i and j with $d_{i,j}$; w_i is computed accordingly to the relationship

$$w_i = \min_{\substack{j=1 \\ j \neq i}}^N d_{i,j} \quad (1)$$

for $i = 1, \dots, N$, where $N = 505$ is the number of observed landslides in the considered time interval. The sample frequency dis-

tribution of w_i , computed for the experimental data is shown in Figure 11, along with the 90% confidence envelope of the frequency distribution of w_i computed on the 100 random sets of 505 landslides. It can be seen that we cannot reject the hypothesis that the minimum distance among landslides is slightly lower in the experimental basin at the 90% confidence level. Even at a 98% confidence limit, some clustering is still apparent in the experimental data. This latter outcome confirms that both spatial ordering as well as randomness contribute to the stochastic nature of slope failures in our experimental landform.

Our analysis above does not take into account the relation of failures to knickpoint locations. We know that knickpoints account for a significant amount of incision in our basin, and hence they should contribute to destabilization of hillslopes. We quantify their effect by focusing on failures along a single channel and counting the number of landslides that occurred upstream and downstream from knickpoint locations. This resulted in 47 failures downstream and 13 failures upstream from knickpoint locations. Clearly, the greater number of landslides downstream could be evidence of knickpoint triggering. However, this could also result from knickpoint location. For instance, a concentration of knickpoints in the upper part of the trunk stream could result in a high number of downstream hillslope failures even if landslides were randomly distributed.

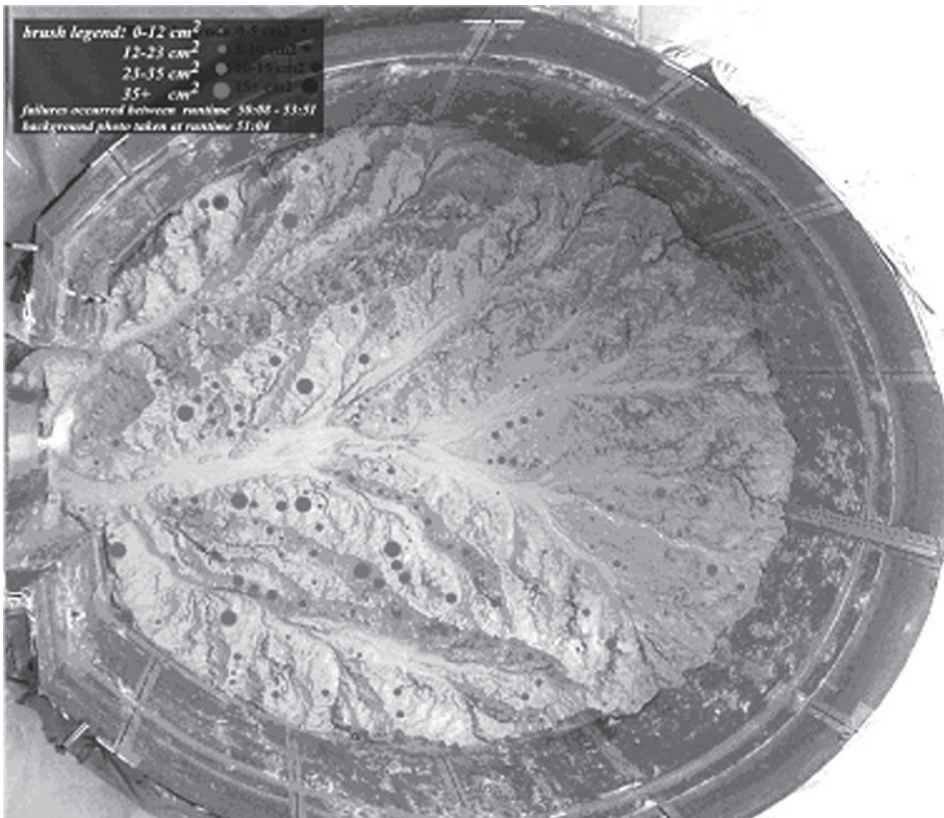


Figure 10. Hillslope failures that occurred during a 4 h period (from 50:08 h to 53:51 h), plotted as gray circles onto a photograph taken at the beginning of the 4 h period, with area proportional to actual failure area. Some clustering of failures is apparent in the photograph; see text for analysis of the significance of this clustering.

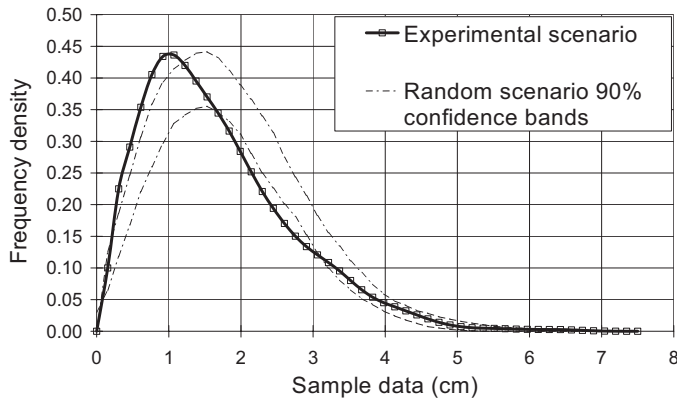


Figure 11. Comparison between the sample frequency distributions of the minimum distance between landslides for experimental and Monte Carlo simulated landslides. Random and experimental distributions are similar. However, the peak frequency at 1 cm separation distance suggests tighter clustering for experimental landslides.

We performed an initial test on the size of failures upstream and downstream from a knickpoint to test for any bias in the actual volume of material removed by failures. Are failures downstream from knickpoints larger than upstream? In order to check from a statistical point of view whether or not significant differences exist, the probability density functions of upstream and downstream landslides were estimated. Figure 12 shows the obtained sample probability density functions. A quantitative comparison was carried out between the mean values and the standard deviations of the two distributions. The 90% confidence limits of the estimated mean values of upstream and downstream hillslope failure areas are 11.81–20.91 cm² and 13.98–19.24 cm², respectively. The 90% confidence limits of the estimated stan-

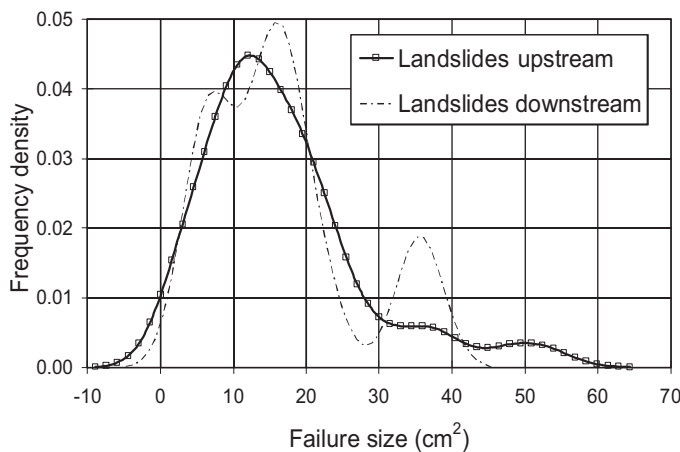


Figure 12. Comparison between the sample frequency distributions of the landslide area (that is, size) that occurred in the main channel upstream and downstream of knickpoints.

ard deviations of upstream and downstream hillslope failure areas are 7.56–15.16 cm² and 9.42–13.32 cm², respectively. Since mean and standard deviations between the two populations overlap substantially, one cannot reject (at the 90% confidence level) the hypothesis that mean and standard deviation of upstream and downstream landslide areas are identical. The similarity of the two probability density functions is also clearly shown in Figure 12. This analysis allows us to conclude that no significant link exists between landslide size and knickpoint location.

We then turned to analyzing the significance of increased numbers of landslides downstream from knickpoints by means of another Monte Carlo simulation. Since landslide area statistics are invariant upstream and downstream from knickpoints, the number of landslides is directly related to total landslide area. We generated 100 random data sets of an equal number ($N = 60$) of hillslope failures along the trunk stream and computed the mean and 90% confidence bands for downstream events. The results are reported in Table 2. The mean number of downstream landslides in the Monte Carlo experiments is 40, with a 90% upper confidence limit of 44. This is slightly lower than the experimental result ($n = 47$). Therefore, one cannot reject the hypothesis, at the 90% confidence level, that downstream landslides occur less frequently in the random scenario than in the experimental basin. Indeed, the above hypothesis cannot be rejected for a confidence level up to 98%.

So, we further focused our efforts by considering the along-stream distance x_i between a knickpoint at time t (the time each photograph was taken) and the experimental landslides at the same time t that occurred downstream on the trunk stream. We then repeated the Monte Carlo analysis by developing 100 sets of 47 downstream randomly located events, while maintaining the same knickpoint positions as observed in the experimental run. This allowed us to get 100 sets of 47 random distances, which we designate with the symbol x_i^* .

A comparison between the experimental probability density functions of x_i and the 90% confidence envelope of the Monte Carlo-generated probability density functions of x_i^* is shown in Figure 13. Clearly, the probability density function of experimental landslides is significantly different in this scenario from that obtained with a random distribution. In the Monte Carlo simulations, the probability density function is unimodal. The mode

TABLE 2. NUMBER OF LANDSLIDES LOCATED DOWNSTREAM AND UPSTREAM OF KNICKPOINTS IN THE RANDOM AND EXPERIMENTAL LANDSLIDE DISPLACEMENT MODELS

Landslide displacement	Number of landslides downstream from a knickpoint	Number of landslides upstream from a knickpoint
Random (100 simulations)	40 (36–44)	20 (24–16)
Experimental	47	13

Note: For the random location, the mean values computed in 100 simulations are given, along with the respective 90% confidence limits (shown in parentheses).

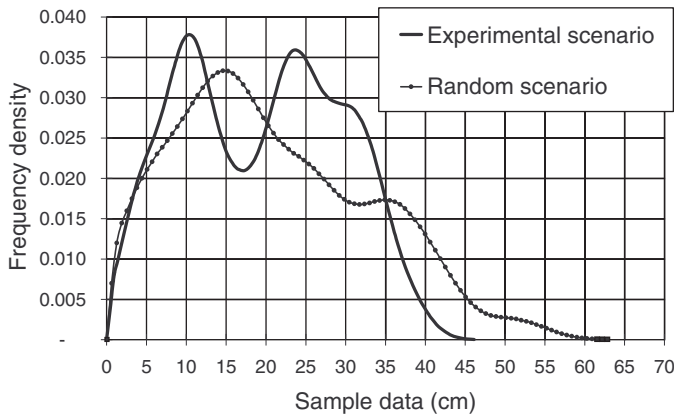


Figure 13. Comparison between the sample frequency distributions of the distances between landslides and closest upstream knickpoint in the experiment and in the random displacements. Experimental frequency distribution is bimodal, with peaks at 10 and 24 cm. A random distribution exhibits a single peak at 10 cm.

of the distribution, x_m^* , indicates the most probable distance between knickpoints and downstream landslides if the locations were random. The magnitude of x_m^* is determined by the geometry of the system and the statistical behaviors of the above stochastic processes. For instance, a knickpoint moving with lower velocity in the upper part of the basin would lead to a smaller value of x_m^* .

The experimental data are characterized by a bimodal probability density function. The value of the first mode, x_1 , is close to the value of x_m^* , which is suggestive of significant landslide triggering unrelated to knickpoints. However, the presence of a second mode, x_2 , suggests the possible presence of a landslide triggering effect induced by knickpoint migration. The parameter x_2 is a characteristic distance between knickpoints and downstream hillslope failures induced by them. The value of x_2 is ~ 24 cm and represents a delay distance between the passage of a knickpoint and landslide activation. The hypothesis of the presence of statistically significant differences between the probability density functions of observed and simulated x_i^* cannot be rejected for a confidence level up to 99%.

We performed one final analysis on the relationship between failures and knickpoint locations. For the i th landslide in the main channel that collapsed during the last 13 h of the experiment downstream from a knickpoint, for i ranging from 1 to 47, the distance h_i from the basin outlet was recorded, as well as the distance k_i from the basin outlet to the closest upstream knickpoint. Therefore, 47 couples (h_i, k_i) were collected. If a relationship exists between h_i and k_i , one would expect to see a significant cross-correlation between them. Indeed, the cross-correlation coefficient between the couples (h_i, k_i) is 0.65. We performed a Monte Carlo simulation as a null hypothesis by computing the cross-correlation coefficient between the vector of the k_i values and 1000 vectors obtained by randomly generating the h_i dis-

tances, from a uniform distribution, in the range $[0, k_i]$, thereby breaking the connection between the locations of landslides and the corresponding knickpoint closest upstream. We generated a sample of 1000 values of cross-correlation coefficients between knickpoint positions and randomly distributed downstream landslides. The mean value of the sample is equal to 0.45 and the upper 90% confidence limit is 0.59. The observed value of the cross-correlation coefficient was exceeded in 6 out of 1000 synthetic random realizations. Therefore, one cannot reject the hypothesis of the presence of a significant relationship between knickpoints and downstream landslides positions at the 99% confidence level. This analysis confirms the findings obtained with the previous investigations.

DISCUSSION

We conducted our experiments under steady rainfall and base-level fall conditions. This effectively removed landslide triggering events, such as severe storms and earthquakes, from consideration, and allowed us to focus on stream incision as the dominant triggering mechanism. In a landscape where streams incise continuously at a constant rate, one might expect that hillslope failures would occur as local conditions for instability are met, and a spatial pattern of landslides independent of knickpoint position would result. If stream incision varies in a systematic way, such as that which occurs during upstream migration of a knickpoint, failure patterns should exhibit clustering downstream from the knickpoint. Interestingly, a synoptic basin-scale view of failures in our experiment revealed a statistically significant tendency to clustering at the 98% confidence level. In particular, by selecting failures along a stream and correlating failure locations with knickpoint locations, we observed a statistically significant link. In particular, we find that hillslope failures are more likely to occur downstream from a knickpoint.

In fact, the results of the three quantitative analyses we carried out to test the hypothesis that stream incision by migrating knickpoints can impose a spatial and temporal pattern on landslide distributions are consistent. They show that one cannot reject the above hypothesis with a confidence level ranging from 98% and 99%. Therefore, a high probability exists that a significant relation between knickpoint and landslide positions is indeed present, even if this result must be interpreted in a statistical sense, i.e., the relation is likely to be present but not certain. The significance of this conclusion, which comes from three different analyses that ended up with consistent results, can be evaluated in view of its confidence level, which is an indication of how strong the relation is. Of course, the spatial pattern of landslides is also affected by the presence of significant hillslope triggering factors that are not related to knickpoint migration.

We offer the following exercise to get some sense of the knickpoint contribution to overall stream incision. Recall that we conducted our experiment at steady base-level fall under flux steady-state conditions. This implies that, on average, stream incision is equal to the base-level fall rate, in this case

3.1 $\mu\text{m/s}$. Under these conditions, we can estimate the contribution of knickpoints to overall stream incision. We observed 12 knickpoint events during the time that we measured knickpoint and hillslope failure locations. During this observational time (13 h), base level dropped 14.5 cm. While knickpoint heights varied, and most knickpoints initiated at a location upstream from the outlet, we can nonetheless set limits on knickpoint contribution by assuming that the average knickpoint height was 0.5 cm, and that this height was maintained while the knickpoint propagated through the entire stream network. Given these assumptions, knickpoints account for 6 cm of incision, or nearly half of the total stream incision during the observation period. If stream incision by knickpoints is the only destabilizing factor, then this implies that knickpoints are responsible for $\sim 50\%$ of the failures. When we compare this estimate to the number of failures downstream ($n = 47$) from a knickpoint to the total failures along the stream ($n = 60$), we find a higher percentage (78%). Note that this calculation likely includes some failures that result from steady stream incision downstream from the knickpoint. The point we make here is that streams incise in our experiment via both knickpoint propagation and steady bed lowering. Given these two mechanisms of incision, it is not surprising that the relationship between knickpoint and failure locations is statistically significant. We can also conclude that knickpoint incision plays a significant role in destabilizing hillslopes.

The rather large mean separation distance (24 cm) we observed between knickpoints and landslides triggered by them is somewhat surprising. This could represent the time required for base-level lowering in the channel to propagate laterally to the toe of the hillslope (recall that channels typically narrow and deepen around a knickpoint). Hillslopes adjacent to channels in v-shaped valleys that lack a floodplain would respond more rapidly to stream incision than hillslopes bordering wide valleys. As far as landslide area is concerned, we did not find any significant difference depending on knickpoint position. As a matter of fact, the probability density functions of hillslope failure size were not significantly different for events downstream and upstream from knickpoints. This outcome seems to indicate that the landslide size in our experiment was not significantly different for events triggered by knickpoint migration than by other causes.

Do natural eroding drainage basins behave like our model? This, of course, we cannot answer definitively. Our experiment was not a scaled model of a natural prototype. In fact, it is not possible to construct a scale model with the linear dimensions of our tank that captures the flow conditions of a larger drainage basin (see Peakall et al., 1996, for an overview of scaling issues in experimental geomorphology). Our experimental streams are dominated by laminar flow (maximum Reynolds number is ~ 750), whereas natural mountain streams are always turbulent. We do observe significant overlap in Froude numbers between experimental and natural drainages (both are dominantly subcritical, with some stream sections at or above critical

flow). Sediment concentration for the experiment we present here approached 25%, and such concentrations are unusual in natural rivers (though not unheard of). Feedback between local deposition and erosion may be enhanced at this concentration and could be a source of instability within model streams (Hasbargen and Paola, 2000). Flow depth to grain size ratios vary downstream in our experiment, but for flow depths on the order of 1 mm, this ratio was ~ 20 . Natural streams typically have much higher ratios. A gravel-bedded stream with 1 cm grains and 1 m depth, for instance, has a depth to grain size ratio of 100. Our goal was not to build an exact replica of a natural landscape, but to represent the major processes in a setting in which we could isolate and analyze landscape interactions that would take an extremely long time in nature. We do not think that any of the scale effects noted above would cause qualitatively different dynamics between knickpoints and landslides. The presence of additional features and processes in a landscape, such as vegetation, gophers, tree throw, creep, weathering and soil development, storm and earthquake events, road construction, etc., would add greater complexity to natural systems. One would expect such effects to complicate and obscure stochastic interactions between streams and hillslopes. While there are significant differences between our model landscape and natural settings, the approximate similarity of landscape features and of process activity (failure sizes on the order of the hillslope length; hillslopes of $\sim 90\%$ slope; knickpoint heights on the order of several flow depths) suggests that natural landscapes experiencing stream incision and knickpoint propagation might also exhibit similar dynamics. Indeed, increased numbers of failures downstream from knickpoint have been noted in natural settings (see Stock and Dietrich, 2003, their Figure 5A; K.X Whipple, 2003, personal commun.).

Our results shed light on the role of stream incision in destabilizing hillslopes. In the absence of external stochastic triggers, such as storm events and earthquakes, we still find that hillslope failures are strongly stochastic. Part of the variability can be ascribed to local conditions, such as slope steepness, pore fluid pressure, past history of failures, etc. Part of the control on landslides, however, is exerted by conditions at the toe of the hillslope. Stream incision, either via steady downcutting or by episodic knickpoint propagation, can introduce a weak structure to spatial patterns of landslides.

Our results suggest that spatial patterns of hillslope failures could be a result of recent incision by streams at the toe of the hillslopes. This observation, which must now be checked against natural settings, could allow for rapid identification of regions in a drainage basin prone to increased landscape instability. For anyone concerned with landslide forecasting in mountainous landscapes, locations downstream from knickpoints merit special attention.

CONCLUSION

We have presented the results from a small-scale erosion experiment under steady forcing conditions where we focused

our attention on the relationship between hillslope failure activity and knickpoint migration. We measured landslide sizes and locations and knickpoint locations over time under steady forcing conditions. We tested the possible existence of spatial organization of hillslope failures, such as clustering, using randomly generated spatial distributions of landslides as a reference. We observed a statistically significant relation between knickpoint positions and downstream landslide location. The detection of a significant link between migrating knickpoints and landslides confirms our intuition concerning the effectiveness of knickpoints in triggering failures. We note, however, that stream downcutting in the absence of knickpoint propagation, and local effects like slope and pore pressure, also control hillslope stability. These effects superimpose a random spatial component onto the spatial patterns associated with knickpoint migration.

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