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Drainage basin evolution in the Rainfall Erosion Facility: dependence on initial conditions

Jon D. Pelletier*

Department of Geosciences, University of Arizona, 1040 E. Fourth St., Tucson, AZ 85721, USA

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Abstract

Four experiments in alluvial drainage basin evolution were carried out in the Rainfall Erosion Facility (REF) at Colorado State University to investigate the dependence of basin evolution on initial topography. Basins were initially undissected. Each experiment began with a unique initial condition representing various end-members of relief and hypsometry. Drainage network development, hillslope processes, basin denudation, and basin response to base-level lowering all depended strongly on the initial topography. No classic model of drainage network evolution was found to be generally applicable. Initially, planar slopes first developed subparallel channels that extended headward dendritically during an early phase of extension. Channel incision occurred first in the interior of the basin where saturation overland flow was greatest, not at the basin outlet as assumed in most classic models of network development. Channels widened over time, initiating lateral migration and drainage capture in the downslope portion of the watershed before transferring lateral migration upslope. Planar basins of larger initial gradient grew headward more quickly and become more deeply entrenched, inhibiting late-stage lateral migration. An experiment with initial relief concentrated at a plateau edge evolved in several unique ways. A high ratio of subsurface-to-surface flow gave rise to mass movements at the plateau edge and outlet channels. Deep channels were quickly cut initially but did not extend far upslope because slope instability undermined channel head migration, leaving the plateau undissected and hence very slow to erode. These results suggest that the distribution of relief within a basin exerts an important control on drainage network pattern and basin denudation. In addition, erosional basins may evolve in several distinct modes characterized by particular combinations of hypsometry, hillslope processes, and mean denudation rate.

Keywords: Flume experiment; Drainage network; Landform evolution

1. Introduction

Flume experiments have added greatly to our understanding of the complex dynamics of the fluvial system (Schumm et al., 1987). Although flume experiments are greatly simplified models of larger-scale drainages, they suggest ways in which elements of the fluvial system couple and give rise to complex dynamics even in the absence of external forcing. Although flume experiments are no substitute for field studies, field work often cannot easily address questions of how landforms within the fluvial system evolve and interact through time, particularly at large scales. Although processes acting in a flume may be different than those of larger basins, the similarity of form between natural basins and model basins in large flumes suggests that the natural and large model basins are at least qual-

* Tel.: +1-520-626-2126.
E-mail address: jon@geo.arizona.edu (J.D. Pelletier).

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itatively similar. Flume experiments provide null hypotheses against which phenomena associated with tectonic or climatic change can be tested. They also suggest dynamic feedback mechanisms between elements of the fluvial system that may not be apparent in field studies in which landform evolution can only be partially reconstructed. In addition, flume studies may act as reality checks on the numerical simulation models of basin evolution now being widely applied. If a model cannot adequately reproduce the behavior of the controlled conditions of a flume, it is unlikely to be relevant to natural landscapes in which much greater complexity is undoubtedly at work. The behavior of numerical and flume models can be directly and precisely compared because initial conditions can be designed in both cases with a high degree of similarity. In addition, both modeling methods permit measurement of any surface position or boundary flux at nearly any point in the experiment, providing a high potential for the collection of spatially and temporally complete data on model landform evolution.

Perhaps the most influential flume experiments on basin evolution have been performed in the Rainfall Erosion Facility (REF) at Colorado State University by Stan Schumm and his students (Parker, 1977; Schumm et al., 1987; Wood et al., 1993; Koss et al., 1994). This work is notable, in part, because the scale of the physical model, 138 m^2 of catchment area, is large enough that the model can be considered to be a prototype of a small alluvial basin (Parker, 1977). This size generates sufficient discharge to reproduce realistic landform features, including diffusive (rainsplash-dominated) hillslopes, meandering channels, and fluvial terraces with a wide range of spatial scales (Parker, 1977). Parker (1977) performed two experiments in drainage network evolution with basins of different relief. The early part of his experiments focused on mean basin denudation (sediment yield) while basin response to base-level lowering was the focus of later stages. Parker observed his low-relief basin to evolve by headward growth with simultaneous branching while his higher-relief basin evolved with the rapid formation of a master rill with subsequent side branching. Notably, however, Parker began both of his experiments with two planes intersecting to form a central valley along the length of the flume in order that runoff could be directed to a predetermined outlet point. As such, Parker's networks were biased to grow in the manner he observed. The formation of parallel rills draining to multiple outlet points, for example, would have been impossible in his experimental setup.

Several theoretical models have been introduced for drainage network development. Glock (1931) postulated several phases of development during network evolution including drainage density reduction as overall basin relief decreases during the tectonic quiescence following initial uplift. Horton (1945) introduced a model in which parallel rills developed with a spacing related to the critical distance for overland flow. A network developed in his model by successive rill piracy and cross-grading of the surface as the largest rill downcut faster than adjacent rills and captured drainage. Drainage capture led to enhanced downcutting in a positive feedback process. Howard (1971) proposed that a wave of dissection penetrated the landscape at channel heads. In his model, the drainage network expanded into undissected portions of the basin leaving behind a mature network as it proceeded. Dunne (1980) presented a model based on subsurface flow and seepage erosion. In his model, first-order channels grow headward by seepage erosion. Deflected subsurface flow toward the channel head then enhanced seepage erosion in a positive feedback process. Parker's (1977) results on drainage network evolution have been taken as evidence that Howard's (1971) model is appropriate for basins of low relief while the rapid development of a master rill with subsequent network extension and elaboration is more likely in higher-relief basins. A principal goal of our work was to expand on Parker's study of drainage network evolution by including different initial hypsometries in addition to variable relief between experiments. Also, we wished to determine the effects of a uniform base level along the lower boundary in addition to the concentrated outlet point Parker used.

In addition to the results on drainage network evolution, Parker (1977) and Schumm et al. (1987) introduced the concept of complex response. Complex response refers to the damped, oscillatory variation in sediment yield Parker observed in the phase of his experiments investigating basin response to base-level lowering (Parker, 1977; Schumm et al., 1987). Although still not well understood, Parker (1977) introduced a schematic model for complex response involving a coupling between the mainstem channel's longitudinal profile and its cross-section. In Parker's model, base-level lowering creates a concentration of stream power and subsequent incision at the basin outlet that increases sediment yield. Propagation of the knickpoint upslope shifts the locus of incision while the downslope reach widens, providing accommodation space for the storage of sediment from upstream as a fill terrace. This results in a local minimum in sediment yield according to the model. Progradation of deposited sediment partially rejuvenates the channel gradient at the outlet leading to another maximum in sediment yield. Complex response is one possible explanation for cut-and-fill terraces observed in natural drainage networks. Few terraces mapped in the field, however, have ever been attributed to this process (see Ethridge et al., 1998 for a review of those that have). A key research question is how to distinguish terraces formed by autocyclic processes or complex response from those generated by external forcing, such as variations in climate or tectonism. Can bounds be placed on the magnitude or time scale for the creation of terraces by autocyclic mechanisms to help distinguish them from those created by allocyclic processes? Another goal of our experiments was to shed light on complex response and, in particular, determine whether it was robust to variations in initial conditions of the basin.

Many more basic questions of landform evolution remain that can be addressed with physical models. The relationship between basin shape, drainage pattern, and denudation, for example, is poorly known. Although many studies have concluded that sediment yield is most strongly correlated with mean basin relief (Ahnert, 1970; Jansen and Painter, 1974; Pinet and Souriau, 1988; Milliman and Syvitski, 1992; Summerfield and Hulton, 1994), sediment yield may be most directly controlled by discharge, grain size, and outlet channel gradient (Dade and Friend, 1998), all of which generally correlate with mean basin relief on a global average but may vary substantially from that average trend. High-elevation plateaus, for example, ought to erode rapidly based on the correlation between sediment yield and elevation. Cosmogenic dating, however, has shown that erosion rates on plateaus are generally very low regardless of climate (Bierman, 1994; Bierman and Caffee, 2001; Granger et al., 2001), suggesting that they erode slowly because of their low average hillslope relief and low drainage density. Rainfall erosion experiments can enable the relationship between basin morphology and sediment yield to be precisely determined for an alluvial basin under conditions of constant runoff and erodibility. Physical models can suggest potential controlling factors that would be difficult to assess in natural basins given the large number of variables that often cannot be measured or controlled for.

Flume experiments can also serve as constraints for computer simulation models of landform evolution. Simulation models of landform evolution, although widely applied to a variety of problems, have done a poor job thus far of enhancing our basic understanding of landscape dynamics. Most fluvial landform evolution models currently in use have a number of basic limitations. In addition to other problems, simulation models often use a fixed, uniform grid on which channels cannot migrate laterally or meander. Lateral migration may be a crucial means of basin adjustment in many alluvial environments, particularly those subject to tectonic forcing (Schumm et al., 2000). Channel widths in most models are also assumed to be fixed in time, preventing any cut-and-fill behavior or any mechanism for the generation of fill terraces. In addition, the empirical relationships describing sediment transport in landform evolution models are poorly constrained. Flume experiments may enable a better constraint to be determined by quantitatively relating sediment flux to channel morphology during an experiment. Certainly, landform evolution models will continue to improve and will soon adequately represent a wide range of processes and forms. Careful validation of these models, however, will become even more important as their complexity grows. If a model can reproduce the essential aspects of flume experiments under a variety of initial conditions, we can have more confidence in its ability to predict the evolution of natural landscapes. Thus, an final motivation for our experiments was to provide numerical modelers with a database, building on the work of Stan Schumm and his students, for comparing the processes and results of their models to a prototype alluvial basin under carefully controlled conditions.

2. Facility description

Four experiments were conducted in the REF, a 15×9.2-m enclosed flume (Fig. 1). Smaller “table

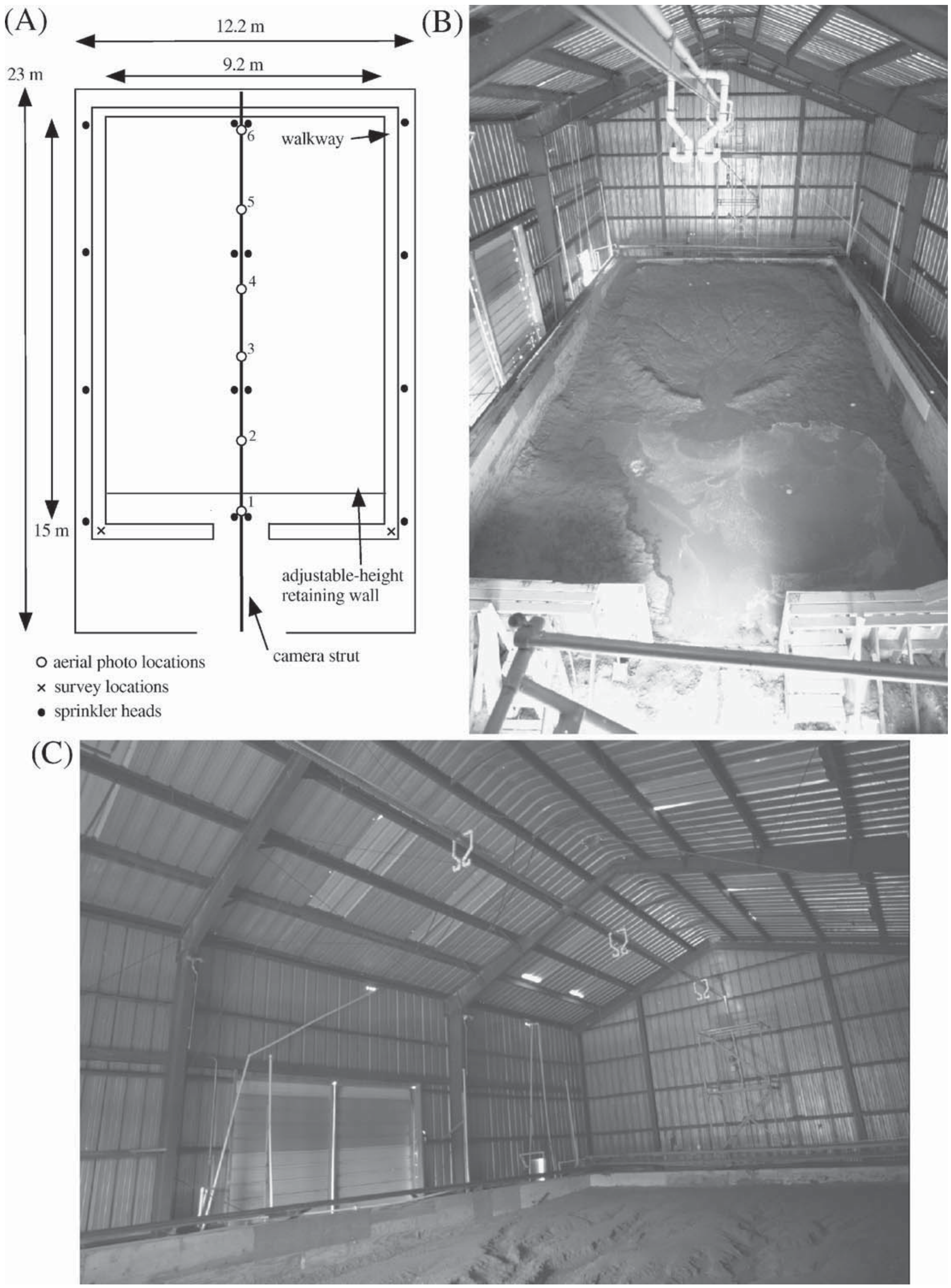


Fig. 1. Configuration of the Rainfall Erosion Facility (REF) for these experiments. (A) Schematic diagram of REF with dimensions. (B) Oblique aerial view looking upslope. Camera strut is in the immediate top foreground. (C) View of strut and pipe system from ground level.

top" basins have been used successfully to model landscapes with high relief and landslide-dominated hillslopes (Crave et al., 2000; Hasbargen and Paola, 2000), but away from the landslide-dominated regime, they are less likely to reproduce the range of processes and landforms observed in natural fluvial systems.

Although the results we will present in this paper are qualitative observations of the basin development only, a primary goal of our experiments was to obtain high-resolution digital images in full stereo coverage for the production of orthophotos and DEMs of the basin surface. A 23-m-long strut with sliding trolley was built and suspended from the ceiling for this purpose (Fig. 1B). A Nikon D1 digital camera was mounted to the trolley, and its position was adjusted with a block-and-tackle counterweight providing tension. Photogrammetry can produce DEMs in the REF with a horizontal resolution of 5 mm and a vertical accuracy of 1 mm using the D1 camera. Precise ground control points are necessary to extract high-quality DEMs. Ground control points and aerial photographs were obtained in our experiments at regular intervals, during which the artificial rainfall was stopped. The intersection method of surveying with two theodolites with known separation distance was used to obtain precise ground control points of the surface. Because each photogrammetric survey requires lengthy processing, the results of those analyses have not been completed. With those data, however, we hope to address questions of the volumetric sediment flux and its controls as well as the storage of sediment in various parts of the fluvial system through time in a future paper.

A new sprinkler system was required because of deterioration of the system used in previous experiments. Fig. 1B and C illustrates the construction of the new sprinkler system and camera strut. The sprinkler system used 1.5-in. (38.1-mm) diameter PVC pipe. Care was required in designing the new system because rain dripping from the camera strut would have caused the formation of a rainsplash gully below. Fig. 1B and C illustrates the construction of the sprinkler system and camera strut. Our solution was to use 16 adjustable-angle sprinkler heads along the borders of the facility and along the central strut. Sprinkler heads along the central strut were adjusted to provide 180° of rainfall pointing away from the strut. In order to minimize the distance between sprinkler heads along the central pipe and still make room for the camera, we used a "two-flamingo" design (named because the PVC pipe was assembled to look like two upside-down flamingos facing away from each other). This small gap between sprinkler heads did not lead to a significant reduction in precipitation intensity because the side sprinklers had sufficient range to cover the center of the basin. Precipitation was calibrated with rain gages on a uniformly spaced grid. Precipitation intensity was found to vary by no more than 10% spatially within a given run or between runs (because of slight fluctuations in water pressure). The areal distribution of intensity was more uniform than Parker's (1977) because we were able to include a central pipe, omitted from Parker's design out of concern for leaks.

Natural lighting from the south side of the building provided proper oblique illumination for the identification of subtle relief in the photographs. Trans-

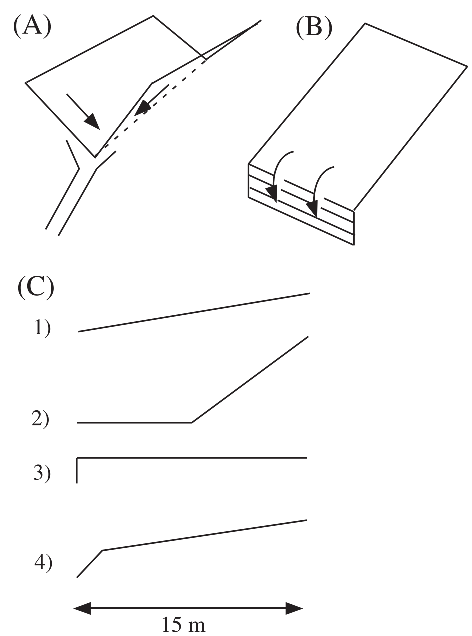


Fig. 2. Initial conditions used in these and earlier experiments in the REF. (A) Parker (1977) used two intersecting planes to concentrate runoff into a pre-defined outlet channel. (B) By constructing an adjustable-height retaining wall made from stacked 2 × 8-in. boards, we were able to provide a uniform linear base level. (C) Profiles of the initial conditions used in our experiments. Topography was uniform along strike in each case. (1) 3% plane, (2) 10% plane with accommodation space for an alluvial fan, (3) plateau with 0.3 m of relief (equivalent to (1)) at plateau edge, (4) 10% plane at downslope end intersecting 3% plane at upslope end.

lucent roof windows were covered with black plastic to minimize more diffused sources of light.

We have modified the boundary conditions of our experiments from the original work of Parker (1977) by constructing an adjustable-height retaining wall inside the original wall (Fig. 1A). This retaining wall enabled planar initial conditions with a uniform base level (Fig. 2B) to be considered rather than a predetermined valley and outlet point as in the Parker (1977) experiments (Fig. 2B). This boundary condition is more appropriate to uniform uplift along a linear fault or eustatic sea level fall. It enabled multiple outlet channels to compete for drainage and migrate laterally.

Approximately 300,000 kg of a homogeneous mixture of fine sand, silt, and clay was obtained from the Lafarge Corporation in Fort Collins for use in the experiments. This was the same source Parker (1977) used in his original experiments (R.S. Parker, affiliation personal communication, 2000). This material is an equal mixture of fine sand, silt, and clay. We did not mix this material with plaster sand as Parker (1977) did because of the success we had in early test runs without the plaster sand. Surfaces were prepared for each experiment with a skid loader for coarse redistribution of sediment, a shovel and wheel barrel for secondary work, and finally a rake and drum compactor for detailed smoothing of the surface.

3. Experimental results

The dominant hillslope process observed in the REF for low-gradient slopes was rainsplash. Larger-gradient, saturated slopes evolved by mass wasting, including slump failure and mudsliding. Channel bank migration was observed to take place by gradual cutting of outer banks in channels of shallow depth and by an episodic process of bank undercutting, slump failure, and reworking of slump material for channels of deeper entrenchment.

We performed four experiments on drainage network and basin evolution. Base level and precipitation intensity were kept constant for the duration of each experiment. After 20 h of simulated rainfall, experiments on basin response to base-level lowering were performed for each basin. The results of the base-level lowering experiments are beyond the scope of this paper and will be described elsewhere. The initial condition of each experiment is illustrated in Fig. 2. Fig. 2A and B contrasts the initial conditions and base-level control used in the original experiments of Parker (1977) (Fig. 2A) with those of our experiments (Fig. 2B). Fig. 2C illustrates the topographic profiles used as initial conditions in our work. Topography was uniform along strike in each case. The initial conditions are: (i) a 3% plane, (ii) a 10% plane with accommodation space for an alluvial fan, (iii) a plateau with 0.3 m of relief (equivalent to (i)) at plateau edge, (iv) a 10% plane at the downslope end of the basin intersecting with a 3% plane at the upslope end. Aerial photographs taken in the early and advanced phases of basin evolution are shown for experiments 1–4 in Figs. 3–7, respectively. Illumination is from and flow is toward the bottom of each photograph. The schematic evolution of experiments 1–4 is shown in Fig. 7A–D, respectively. These figures are included to illustrate the verbal descriptions below.

Experiment 1 evolved from an initially planar slope with a gradient of 3%. The water table rose during the first 30 min of the experiment with no accompanying surface erosion. Saturation overland flow began $\approx$ 2 m upslope from the base level (just beyond the lower photo edge in Fig. 3) after the first 30 min of rainfall. Subparallel channels were quickly incised by this runoff. Contrary to our expectation and the assumption of nearly all classic models, the initial incision was not at the basin outlet but upslope of the outlet where overland flow was greatest (Figs. 3A and 7A, left). Subsequently, channels lengthened and grew headward with simultaneous branching (Fig. 7A, center). Downslope channels widened and shallowed over time and eventually migrated laterally by preferentially downslope bank erosion. Channel widening and development of well-defined flood plains occurred despite constant precipitation intensity. Lateral migration led to drainage capture in the downslope portion of the basin first and gradually moved upslope. The final drainage pattern includes a major confluence in the downslope portion and parallel drainage in the upslope portion of the basin (Figs. 3B and 7A, right). Channel centerlines stabilized by $\approx$ 10 h of applied rainfall. The basin was monitored for an additional 10 h during which continued widening and shallowing were observed. During this time, channel habit changed from mostly meandering to mostly braided.

(A)

(B)

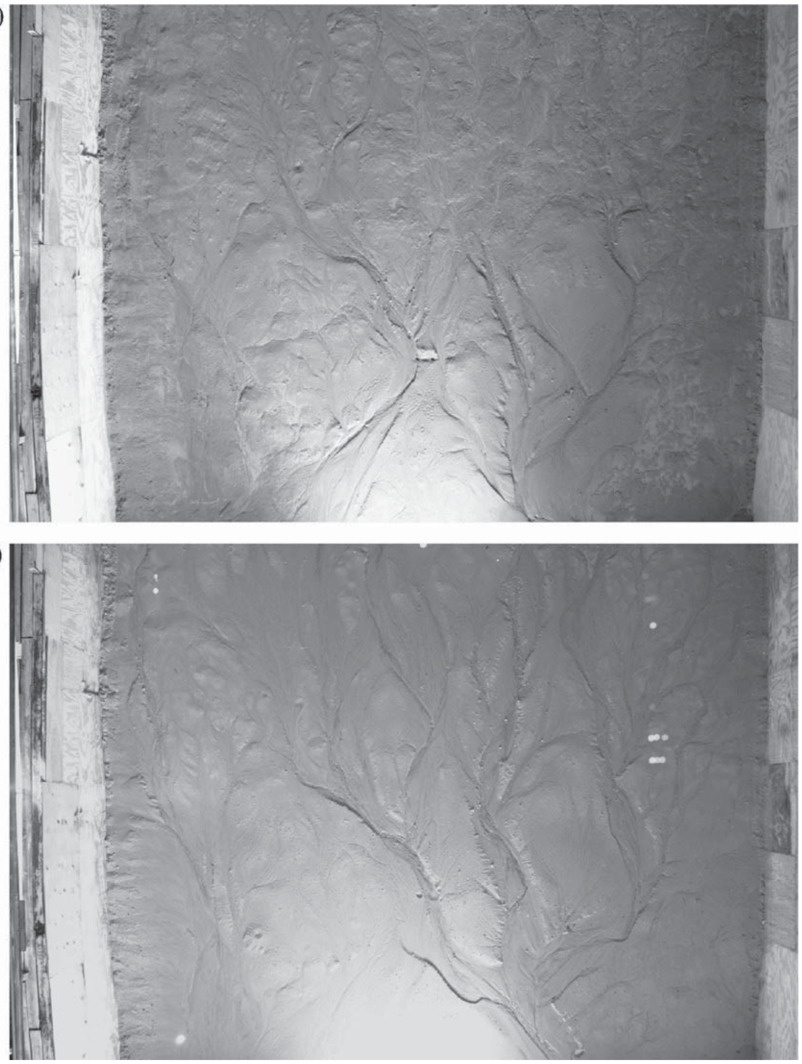


Fig. 3. Early (A) and late (B) configuration of drainage network for experiment (1) (3% plane). (A) Early (elapsed time = 1 h) configuration photographed from aerial photo position 3. Illumination is from and flow is towards the bottom of the photo. (B) Late (elapsed time = 10 h) configuration photographed from aerial photo position 3. See text for details.

Experiment 2 included the erosion of a steep (10%), initially planar slope coupled to a prograding alluvial fan. This experiment differed from the others in two respects: its base level was not held constant (because of fan aggradation), and the substrate differed in composition. The presence of a gradually rising base level did not appear to significantly aspect the basic aspects of the drainage network evolution and erosion. The experiment was affected, however, by the presence of gravel in the substrate. This was the first experiment we ran and several problems were discovered. We were using existing sediment from a prior experiment in that gravel was present which led to channel armoring in this experiment. As such, the later stages of the experiment cannot be easily compared to the results of the other experiments. After this experiment, the gravel-contaminated sediment was removed and new material brought in.

Fig. 4A (Fig. 7B, left for schematic view) illustrates the early (1-h elapsed time) configuration of the

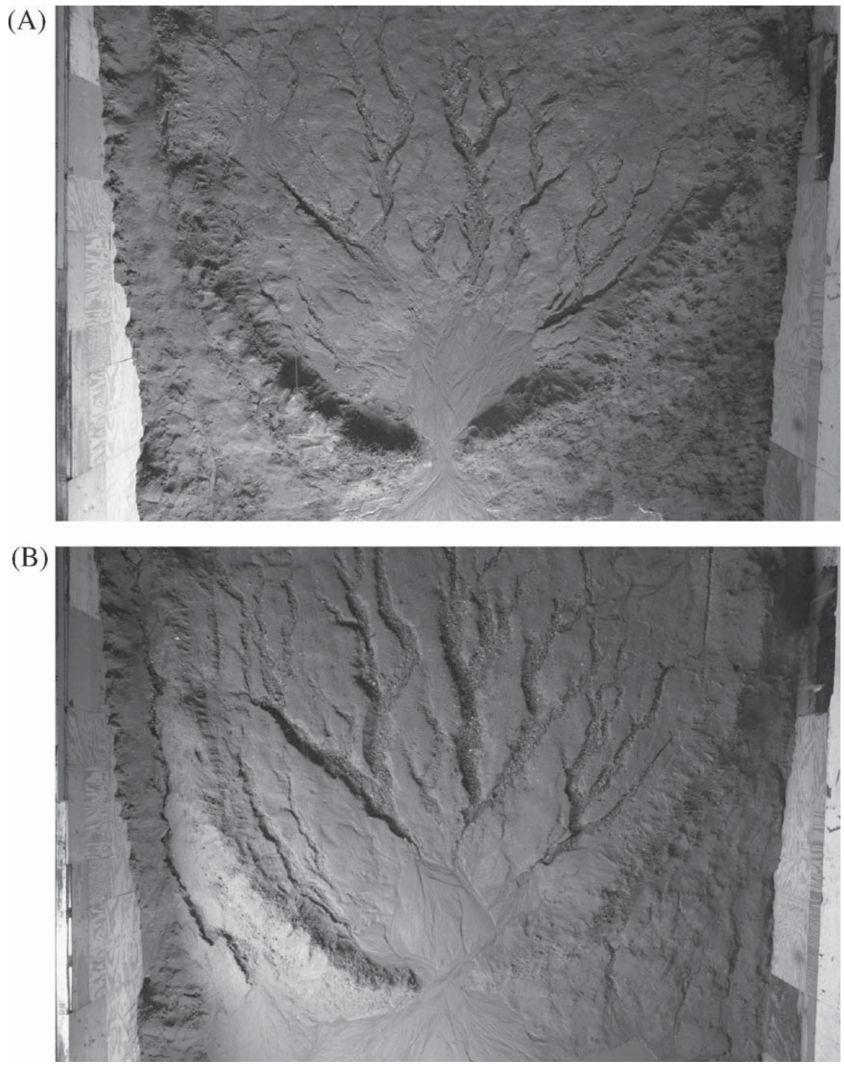


Fig. 4. Early (A) and late (B) configuration of drainage network for experiment (2) (10% plane in upper half of basin, at in downslope half). (A) Early (elapsed time = 1 h) configuration photographed from aerial photo position 4. Channels deepened initially and then widened once gravel layer was exhumed in (B) (5-h elapsed time).

basin of experiment 2. Saturation overland flow began ≈ 20 min into the experiment. A parallel drainage network formed almost simultaneously throughout the basin in essentially its final configuration. The network formed so quickly that no headward growth was observed. Channels deepened at first and then widened once gravel layer was exhumed. Depth of channel entrenchment was significantly greater than in experiment 1. After 5 h, the drainage network was in a stable configuration with only minor drainage adjustment near the fan apex (Figs. 4B and 7B, right).

Experiment 3 began with a plateau with the same relief (0.3 m) as experiment 1. All the relief in this case was concentrated at the plateau edge. Lakes began developing on the surface after ≈ 30 min of rainfall. Two lakes breached the plateau edge in quick succession after ≈ 1-h elapsed time, quickly draining the lakes and forming two deep gullies (Figs. 5A and 7C, left). Gully channel heads migrated upslope but were

(A)
(B)

Fig. 5. Early (A) and late (B) configuration of drainage network for experiment (3) (plateau: at except for sheer 0.3-m drop at base-level boundary condition). (A) Early (elapsed time = 1 h) configuration photographed from aerial photo position 2. (B) Late (elapsed time = 10 h) configuration photographed from aerial photo position 2.

quickly undermined by mud flows that reduced relief at the channel head and eventually surpressed headward migration. Drainage density increased very little after this time, leaving most of the plateau undissected and uneroded for the remainder of the experiment. Over time, the plateau surface was remarkably stable. Channels widened by slow mudsliding but did not migrate or grow headward appreciably. Fig. 5B (Fig. 7C, right for schematic view) shows the configuration of the basin after 10 h. Several processes worked in conjunction to limit the erosion of the uplands and localize sediment production at the plateau edge in this experiment. The negligible gradient of the uplands gave rise to a high ratio of base flow to surface flow. This high ratio increased pore pressures and initiated slope instability along the steep plateau and gully edge, which prevented the maintenance of stable slopes near channel heads. Infilling near the channel head reduced the channel head slope below the critical value for growth. Without dissection, upland erosion was negli-

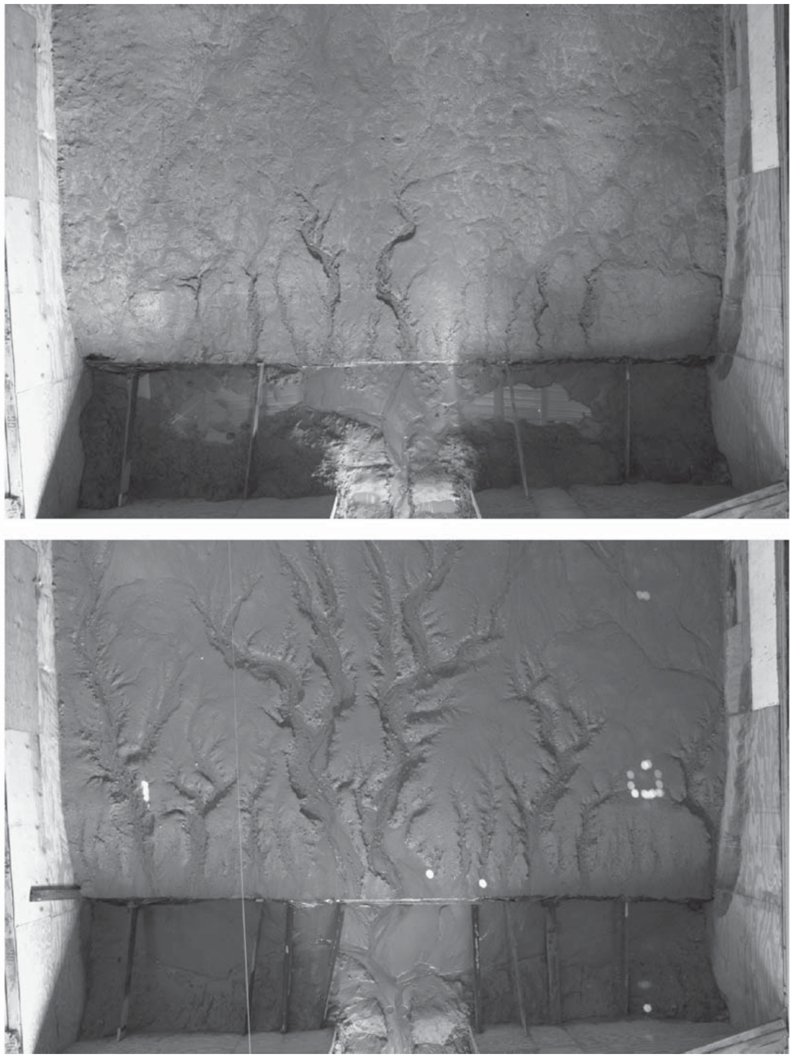
(A)
(B)


Fig. 6. Early (A) and late (B) configuration of drainage network for experiment (3) (10% plane at lowermost 1.5 m of basin intersecting with a 3% plane for remainder of basin). (A) Early (elapsed time = 30 min) configuration from aerial photo position 2. (B) Late (elapsed time = 10 h) configuration from aerial photo position 2.

gible. This experiment illustrated how hypsometry, drainage network morphology, and relief-specific processes can act in a mutually enhancing, positive feedback to drive the basin toward a specific mode of evolution. In this case, that mode is characterized by the maintenance of localized relief and downcutting a high ratio of base flow to surface flow, erosion by mass wasting, and a low mean basin denudation rate.

The final experiment began as two intersecting planes of 10% (downslope, 1.5 m long) and 3% (upslope, 13.5 m long). Parallel rills developed early in the experiment on the steep portion of the basin. Rills in the center of the watershed grew headward more rapidly than those near the walls. Once the central rills developed into the region of lower slope, they grew headward more slowly and with a higher bifurcation ratio. Dendritic drainage developed from the central rills. Once fully established with maximum drainage density, channel centerlines were stable and channels widened and shallowed with time.

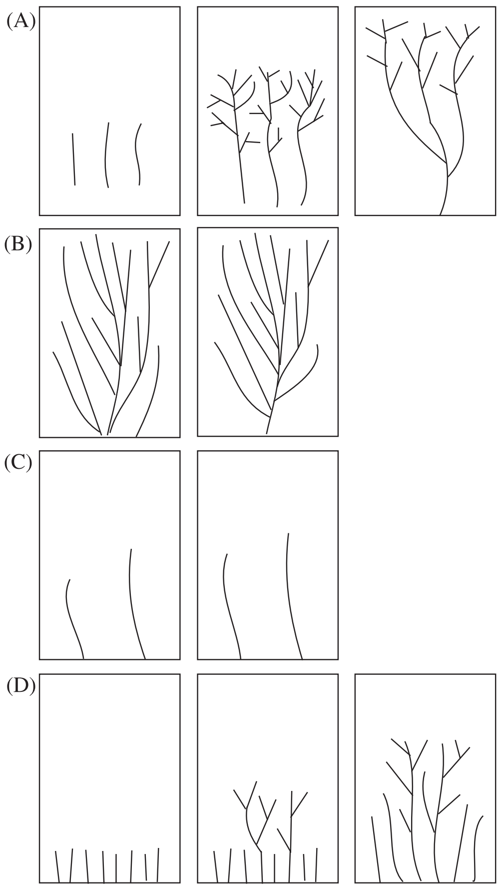


Fig. 7. Schematic evolution of drainage networks in experiments (1)–(4) ((A)–(D)). Elapsed time increases from left to right. (A) Dissection occurred upslope of the base level first as parallel rills. Rills grew headward with simultaneous branching. Lateral migration and drainage capture occurred in the downslope portion of the basin, forcing the upslope portion of the basin to change from dendritic to parallel drainage. (B) Drainage network appeared simultaneously throughout the basin; headward growth occurred too rapidly to be observed. Channel centerlines are stable over time. We postulate that if the base level was held fixed, some drainage capture by the main stem channel would occur. (C) Gullies form rapidly but do not grow headward very far due to undercutting of the knickpoint by slope failure. (D) Rills develop quickly on the steep slope. Rills in the center capture the most drainage and starve the nearby rills of drainage as they expand their catchments. Growth is dendritic on the gentler slope. This contrasts with parallel drainage on the lower-relief basin of experiment (1).

The duration of our experiments was much shorter than the 100 h reached by Parker (1977). Our experiments were ended for practical limitations on how much sediment could leave the REF area, but also because basins had become quite stable compared with earlier times in their evolution as determined by sediment yield and channel changes. The second half of each experiment was characterized by channel centerline stability with increasing width and decreasing flow depth over time. Complex response was not observed as a terrace generating mechanism during our experiments. In the original experiments of Parker (1977), complex response resulted in an oscillation in sediment yield and terrace formation with a time scale of $\approx$ 20 h. Therefore, our experiments may not have run long enough to observe the process. Another possibility is that lateral migration (present in our experiment but inhibited by Parker's experiments) prevented the oscillation of sediment storage and release associated with complex response in our experiments. Nevertheless, our experience in the REF suggests that complex response is likely to be dominated by basin response to allocyclic-forcing mechanisms in many natural basins. Channel responses to base-level fall in the REF and their accompanying increase in sediment yield occurred very rapidly (within minutes), with a return to near-stability on a time scale of several hours in all cases. For example, while 20 h is the time scale necessary to create a terrace through complex response, we observed that a minor base-level lowering can rejuvenate the entire drainage network, incising the network and laterally shifting its channels in under 1 h. While there is likely to be some remaining basin response to perturbation at very long time, the stability of our experiments on these long-time scales suggests that the autocyclic oscillations in a natural basin are likely to much smaller than the response of natural basins to even weak external forcings. In the REF, complex response acts on a time scale much longer and with a magnitude much smaller than basin response to base-level (i.e., tectonic) changes. Coupled with order-of-magnitude changes in Quaternary sediment production in areas such as the SW US (Bull, 1991), complex response is unlikely to be able to create terraces with a high preservation potential in many natural basins.

4. Discussion

None of the theoretical models proposed for the evolution of drainage networks proved to be applicable to our experiments. This is not surprising because none of the models include initial topography or lateral channel migration in any way. Lateral migration was found to be crucial to drainage capture and network integration in our experiments, particularly for basins of low relief. Horton's model of rill formation and subsequent piracy matched some basic elements of the evolution of the initially planar slope. However, stream capture in his model occurred by the elimination of divides through differential rill erosion. Instead, we observed capture to take place largely by preferentially downslope bank erosion. Our results suggest that the initial topography influences drainage network pattern in at least two ways. Initial topography influences how quickly channel heads migrate upslope and the magnitude of the regional slope that must be overcome by local valley downcutting to create a dendritic rather than a parallel drainage pattern. A steep initial slope develops drainage networks rapidly. If the initial slope is planar, a parallel drainage pattern will result because channel heads grow quickly in the direction of maximum drainage. A lower-relief basin is less likely to develop drainage along the regional gradient (and hence a parallel drainage pattern) for two reasons. First, channels grow headward more slowly, enabling them to downcut their valleys, locally distorting the regional gradient. Second, because the regional surface gradient is low to begin with, local valley downcutting between large and small incipient streams can more easily dominate the regional trend and create more dendritic drainage paths responding to the variable local slope aspects of the basin.

Our results suggest that the ratio of base flow to surface flow may be a fundamental parameter of landform evolution. Basins of the High Plains such as the Cimarron and Canadian River basins, for example, are clearly influenced by the presence of the highly permeable alluvial aquifer in the near subsurface (Brice, 1966). These basins have unusually high bifurcation ratios, low ratios of their dissected areas to lengths, undissected upland topography, and high rates of mass wasting by seepage erosion adjacent to the channel. All of these characteristics were observed in our plateau experiment (number 3). We propose that this ''plateau-style'' basin development is one of several distinct modes of landform evolution. Distinct modes of basin evolution exist because certain initial conditions lead to combinations of processes and morphologies that are self-reinforcing. Uniform downcutting of a steep planar basin with parallel drainage may be another fundamental mode of evolution in which rapid development of parallel drainage ensures a relatively uniform distribution of stream power that, in turn, helps to preserve the parallel drainage pattern by maintaining a uniform gradient.

The basin hypsometry and mode of evolution in our experiments greatly influenced mean basin denudation. This observation contrasts with studies that conclude that denudation correlates most strongly with basin relief (Ahnert, 1970; Jansen and Painter, 1974; Pinet and Souriau, 1988; Milliman and Syvitski, 1992; Summerfield and Hulton, 1994). Fig. 8 illustrates how three basins of equal relief but different hypsometries may have different rates of mean basin denudation. Mean basin denudation in this schematic model is assumed to be correlated with mean hillslope relief. This assumes that larger hillslope gradients lead to higher erosion and that the channel system can transport at least some of that enhanced primary sediment supply to the outlet. In Fig. 8A, the basin has a parallel drainage pattern and an even distribution of relief (i.e., a symmetric hypsometric curve). Channel downcutting in this basin will be relatively low because channels in a parallel drainage pattern increase their discharge (and hence stream power) more gradually with increasing length compared with channels in a dendritic drainage pattern. The result is a low maximum hillslope relief but a moderate mean relief (and mean basin denudation) because hillslope relief is consistently moderate throughout the basin. Fig. 8C illustrates the opposite end-member of high but localized hillslope relief. The plateau experiment was the most stable of the four experiments and clearly had the lowest denudation rate. Although the maximum hillslope relief in this case is large, much of the basin remained completely flat and undissected. As a result, the mean basin denudation is low in this case. The highest mean denudation rate is likely to occur for a bowl-shaped basin with dendritic drainage. Dendritic drainage leads to enhanced downcutting relative to parallel drainage and will lead to a higher average hillslope relief and mean basin denudation compared with basins in Fig. 8A or C.

Although conditions in the REF are highly controlled, our results may be directly applicable to the post-depositional erosion of several types of natural

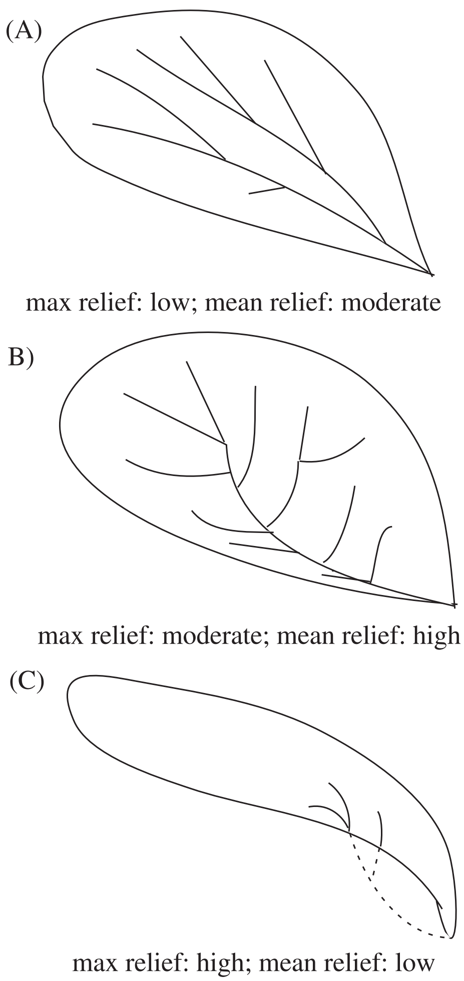


Fig. 8. Schematic diagram of the dependence of mean basin denudation on hypsometry for basins of equal hillslope relief. (A) A steep basin with uniform hypsometry (i.e. similar to experiment 2). (B) A bowl-shaped basin has consistent hillslope relief in the basin (compared to the plateau case (C)) but a larger average hillslope relief than (A) because the dendritic drainage creates rivers with increasing transport capacity downslope and hence substantial downcutting ability. (C) A basin with plateau uplands (similar to experiment 3).

landforms. Piedmont deposits in the Basin and Range Province, for example, are created during episodes of enhanced upslope erosion and piedmont aggradation associated with vegetational successions during glacial–interglacial transitions (Bull, 1991). Repeated avulsion during this aggradation creates a broad, low-relief surface of relatively homogeneous alluvium. When the sediment pulse decreases, deposits become entrenched narrowly at the proximal end of the fan and broadly at the distal end. Entrenchment creates a base-level lowering at the distal end that initiates dissection of the planar surface. The result is a set of natural experiments in drainage network formation that have been ongoing through the Quaternary. These surfaces range in age from roughly 10^4 to 10^6 years in age with a variety of initial gradients, depths of dissection, and alluvial textures. Comparison of drainage networks dissected into these deposits with the results of flume experiments further enhances our understanding of the evolution of drainage networks.

The results we have obtained are only applicable for alluvial basins. Basins with weathering or detachment-limited conditions typically evolve quite differently than alluvial basins. However, because slope retreat and the maintenance of relief are more common for weathering-limited basins than for alluvial basins, some of the general patterns we have pointed out regarding the dependence of basin dynamics on hypsometry may be as important or more important in areas of significant bedrock exposure.

5. Conclusions

Four experiments in drainage network and alluvial basin evolution were carried out in the Rainfall Erosion Facility (REF) at Colorado State University. The initial conditions were modified from the original experiments of Parker (1977) to enable a uniform base level of erosion to be applied to the basin and multiple outlet channels to compete for drainage and migrate laterally. Basins and their drainage networks evolved in markedly different ways depending on their initial topography. Initially planar basins developed parallel rills that lengthened over time and migrated laterally, integrating first in the downslope portion and later in the upslope portion of the basin. Widening and shallowing of these rivers greatly enhanced their lateral mobility. An initially planar basin with a steep gradient rapidly developed entrenched, parallel rills and were more stable during the length of the experiment than channels of the planar basin with lower relief. A basin composed of two intersecting slopes evolved with parallel rilling on the steep slope and entrenched dendritic drainage development on the gentler slope. The greater total relief of this basin resulted in greater entrenchment, reduced lateral migration, and a more dendritic drainage pattern relative to the experiment with a single planar initial slope. A basin with relief concentrated at a plateau edge evolved in a unique way driven by hillslope mass wasting that localized erosion at the plateau edge, maintaining steep slopes and preventing erosion and dissection of the uplands. Our work suggests that initial conditions can strongly determine the processes and dynamics of basin evolution; basins and drainage networks may have several distinct modes of coupled evolution. A better understanding of these modes of evolution may enable geomorphologists to better infer paleolandscape morphology and landform evolution from the modern landscape.

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