GEOMORPHIC THRESHOLDS AND COMPLEX RESPONSE OF DRAINAGE SYSTEMS

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ABSTRACT

The alluvial and morphologic details of drainage systems are much too complex to be explained by progressive erosion alone. Within the constraints of the erosion cycle these complexities (terraces, alluvial deposits) must be explained by external variables such as climatic, tectonic, isostatic or land-use changes. However, field and experimental research into the details of fluvial landform development indicate that some abrupt modifications of such a system can be inherent in its erosional development and that two additional concepts are required for comprehension of drainage system evolution. These are 1) geomorphic thresholds and 2) complex response of drainage systems.

INTRODUCTION

Due to the complexity of Quaternary climatic and tectonic histories, topographic and stratigraphic discontinuities can be conveniently explained as a result of climatic and tectonic events. In this way the compulsion to fit geomorphic and stratigraphic details into a Quaternary chronology is satisfied, as is the basic scientific need to identify cause and effect. As the details of Holocene stratigraphic and terrace chronologies are studied, a bewildering array of changes are required to explain the behavior of a drainage system. In fact, it is now accepted that some major erosional adjustments can be induced by rather insignificant changes in the magnitude and frequency of storm events (Leopold, 1951).

The numerous deviations from an orderly progression of the erosion cycle has led many to discount the cycle concept completely. Current practice is to view the evolutionary development of the landscape within the conceptual framework of the erosion cycle, but to consider much of the modern landscape to be in dynamic equilibrium. There are obvious shortcomings in both concepts. For example, although the cycle involves continuous slow change, evidence shows that periods of relatively rapid system adjustment results from external causes. This, of course, is equally true of geomorphic systems in dynamic equilibrium. That is, for a change to occur in either the cycle or a system in dynamic equilibrium there must be an application of an external stimulus. Hence landscape changes and changes in rates of depositional or erosional processes are explained by the influence of man, by climatic change or fluctuations, by tectonics, or by isostatic adjustments.

One cannot doubt that major landscape changes and shifting patterns of erosion and deposition have been due to climatic change and tectonic influences and that man's influence is substantial. Nevertheless, it is the details of the landscape, the last inset fill, the low Holocene terrace, modern periods of arroyo cutting and gulleying, alluvial-fan-head trenching, channel aggradation and slope failure that for both scientific and practical reasons of land management require explanation and prediction. These geomorphic details are of real significance, but often they cannot be explained by traditional approaches.

Another aspect of the problem is that within a given region all landforms did not respond to the last external influence in the same way and, indeed, some have not responded at all. This is a major geomorphic puzzle that is commonly ignored. If land systems are in dynamic equilibrium conponents of the system should respond in a similar way to an external influence. Hence, the effects of hydrologic events of large magnitude should not be as variable as they appear to be.

The cyclic and dynamic equilibrium concepts are not of value in the location of incipiently unstable landforms because within these conceptual frameworks system change is always due to external forces. There is now both experimental and field evidence to indicate that this need not be true. The answer lies in the recognition of two additional concepts that are of importance for an understanding of landscape development. These may be termed 1) geomorphic thresholds and 2) complex response of geomorphic systems. Basically, they suggest that some geomorphic anomalies are, in fact, an inherent part of the erosional development of landforms and that the components of a geomorphic system need not be in phase.

These concepts are certainly not new, and one need not search long to find a geomorphic paper or book mentioning thresholds or the complexities of geomorphic systems (for example, Chorley and Kennedy 1971, Tricart 1965, Pitty 1971). However, these concepts have not been directed to the solution of specific problems nor has their significance been fully appreciated. The assumption that all major landform changes or changes in the rates and mechanics of geomorphic processes can be explained by climatic or tectonic changes has prevented the geologist from considering that landform instability may be inherent.

THRESHOLDS

Thresholds have been recognized in many fields and their importance in geography has been discussed in detail by Brunet (1968). Perhaps the best known to geologists are threshold velocities required to set in motion sediment particles of a given size. With a continuous increase in velocity, threshold velocities are encountered at which something begins and with a progressive decrease in velocity, threshold velocities are encountered at which something ceases, in this case, sediment movement. These are Brunet's (1968, pp. 14 and 15) "thresholds of manifestation" and "thresholds of extinction", and they are the most common types of thresholds encountered. When a third variable is involved, Brunet (1968, p. 19) identified "thresholds of reversal." An example of this is Hjulstrom's (1935) curve showing the velocity required for movement of sediment of a given size. The curve shows that velocity decreases with particle size until cohesive forces become significant, and then the critical velocity increases with decreasing grain size. Another example of this type of relationship is the Langbein-Schumm (1958) curve which shows sediment yield as directly related to annual precipitation and runoff until vegetative cover increases sufficiently to retard erosion. At this point there is a decrease in sediment yield with increased runoff and precipitation. Perhaps thresholds is not a good word to describe the critical zones within which these changes occur, but it is a simple and easily understood term.

The best known thresholds in hydraulics are described by the Froude and the Reynolds numbers, which define the conditions at which flow becomes supercritical or turbulent. Particularly spectacular are the changes in bed form characteristics at threshold values of stream power.

In the examples cited, an external variable changes progressively thereby triggering abrupt changes or failure within the affected system. Responses of a system to an external influence occur at what will be referred to as *extrinsic thresholds*. That is, the threshold exists within the system, but it will not be crossed and change will not occur without the influence of an external variable.

Thresholds can also be exceeded when input is relatively constant, that is, the external variables remain relatively constant, yet a progressive change of the system itself renders it unstable, and failure occurs. For example, it has been proposed that the progressive erosion of a region will cause short but dramatic periods of isostatic adjustment. With an essentially constant rate of denudation a condition is reached when isostatic compensation is necessary, and this probably takes place during a short period of relatively rapid uplift (Schumm 1963). Somewhat analagous to this is the long period of rock weathering and soil development required before a catalytic storm event precipitates mass movement. Following failure a long period of preparation ensues before failure can occur again (Tricart, 1965, p. 99). These *intrinsic thresholds* are probably common in geologic systems, but it is only *geomorphic examples* that will be considered here.

A geomorphic threshold is one that is inherent in the manner of landform change; it is a threshold that is developed within the geomorphic system by changes in the system itself through time. It is the change in the geomorphic system itself that is most important, because until the system has evolved to a critical situation, adjustment or failure will not occur. It may not always be clear whether the system is responding to geomorphic thresholds or to an external influence, but when a change of slope is involved, the control is geomorphic, and the changes whereby the threshold is achieved is intrinsic to the system.

EVIDENCE FOR GEOMORPHIC THRESHOLDS

Recent field and experimental work support the concept of geomorphic thresholds, and it has been used to explain the distribution of discontinuous gullies in the oil-shale region of western Colorado and to explain channel pattern variation along the Mississippi River.

Discontinuous gullies

Field studies in valleys of Wyoming, Colorado, New Mexico, and Arizona revealed that discontinuous gullies, short but troublesome gullied reaches of valley floors, can be related to the slope of the valley-floor surface (Schumm and Hadley, 1958). For example, the beginning of gully erosion in these valleys tends to be localized on steeper reaches of the valley floor. Carrying this one step farther, with the concept of geomorphic thresholds in mind, it seems that for a given region of uniform geology, land use and climate, a critical threshold valley slope will exist above which the valley floor is unstable. In order to test this hypothesis, measurements of valley-floor gradient were made in the Piceance Creek Basin of western Colorado. The area is underlain by oil shale, and the potential environmental problems that will be associated with the development of this resource are considerable.

Within this area, valleys were selected in which discontinuous gullies were present. The drainage area above each gully was measured on maps, and valley slopes were surveyed in the field. No records of runoff or flood events exist so drainage basin area was selected as a variable, reflecting runoff and flood discharge. When valley slope is plotted against drainage area, the relationship is inverse (Fig. 1), with gentler valley slopes being characteristic of large drainage areas. As a basis for comparison, similar measurements were made for valleys in which there were no gullies, and these data are also plotted on Fig. 1. The lower range of slopes of the unstable valleys coincide with the higher range slopes of the stable valleys. In other words, for a given drainage area it is possible to define a valley slope above which the valley floor is unstable.

Note that the relationship does not pertain to drainage basins smaller than about four square miles. In these small basins variations in vegetative cover, which are perhaps related to the aspect of the drainage basin or to variations in the properties of the alluvium, prevent recognition of a critical threshold slope. Above four-square miles there are only two cases of stable valley floors that plot above the threshold line, and one may conclude that these valleys are incipiently unstable and that a major flood will eventually cause erosion and trenching in these valleys.

Using Fig. 1, one may define the threshold slope above which trenching or valley instability will take place in the Piceance Creek area. This has obvious implications for land management for, if the slope at which valleys are incipiently unstable can be determined, corrective measures can be taken to artificially stabilize such critical reaches, as they are identified.

It seems possible that future work will demonstrate that similar relationships can be established for other alluvial deposits. For example, trenching of alluvial fans is common,and the usual explanation for fan-head trenches is renewed uplift of the mountains or climatic fluctuations. However, the concept of geomorphic thresholds should also be applicable to this situation. That is, as the fan grows it may steepen until it exceeds a threshold slope, when trenching occurs. Preliminary results from experimental studies of alluvial-fan growth reveal that periods of trenching

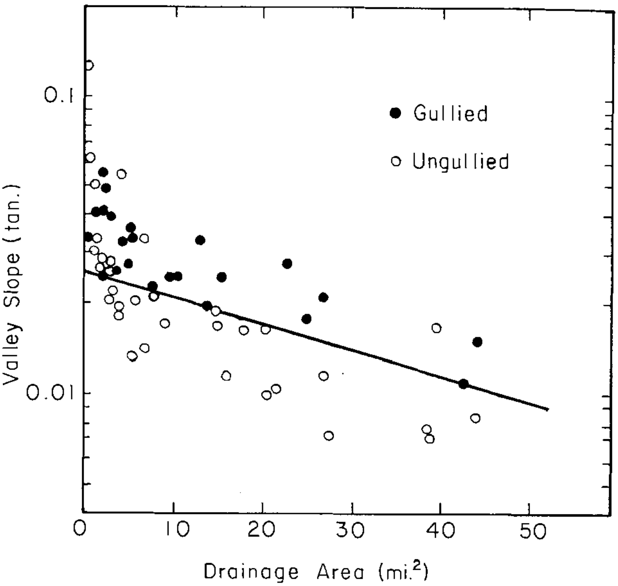

Figure 1. Relation between valley slope and drainage area, Piceance Creek basin, Colorado. Line defines threshold slope for this area (from P. C. Patton, 1973, unpublished M.S. thesis).

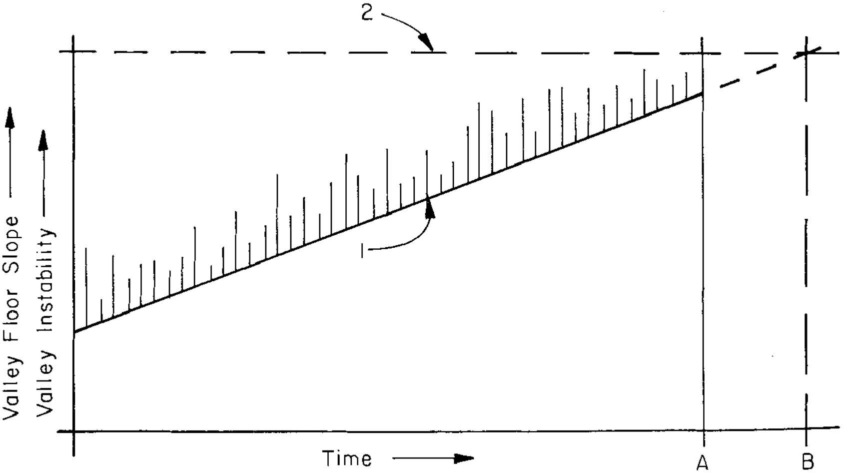

Figure 2. Hypothetical relation between valley-floor gradient and valley-floor instability with time. Superimposed on line 1, representing an increase of valley-floor slope, are vertical lines representing instability of the valley floor as related to flood events. When the ascending line of valley-floor slope intersects line 2 representing the maximum slope at which the valley is stable, failure or trenching of the valley alluvium will occur at time B. However, failure occurs at time A, as the apparent direct result of a major storm or flood event.

The concepts of thresholds as applied to alluvial deposits in the western U.S.A. is illustrated by Fig. 2, where the decreasing stability of an alluvial fill is represented by a line indicating increase of valley slope with time. Of course, a similar relation would pertain if, with constant slope, sediment loads decrease slowly with time. Superimposed on the ascending line of increasing slope are vertical lines showing the variations of valley floor stability caused by flood events of different magnitudes. The effect of even large events is minor until the stability of the deposit has been so reduced by steepening of the valley gradient that during one major storm, erosion begins at time A . It is important to note that the large event is only the most apparent cause of failure, as it would have occurred at time B in any case.

These studies of alluvial deposits in dry lands suggest that large infrequent storms can be significant but only when a geomorphic threshold has been exceeded. It is for this reason that high-magnitude, low-frequency events may have only minor and local effects on a landscape.

River patterns

Experimental studies of river meandering have been performed by both hydraulic engineers and geologists over many years. Such a study was designed to investigate the influence of slope and sediment loads on channel patterns (Schumm and Khan, 1972). It was found, during these experiments in which the water discharge was held constant, that if a straight channel was cut in alluvial material at a very low slope, the channel would remain straight. However, at steeper slopes the channel meandered. As the slope of the alluvial surface on which the model stream was flowing (valley slope) steepened, the velocity of flow increased, and shear forces acting on the bed and bank of the miniature channel increased. At some critical value of shear, bank erosion and shifting of sediments on the channel floor produced a sinuous course. The conversion from straight to sinuous channel at a given discharge occurred at a threshold slope (Fig. 3). As slope increased beyond this threshold, meandering increased until at another higher threshold the sinuous channel became a straight braided channel. The experiments revealed that there is not a continuous change in stream patterns with slope from straight through meandering to braided, but rather the changes occur at threshold slopes. Slope in this case is an index of sediment load and the hydraulic character of the flow in the channel; nevertheless, the relationship can be used to explain the variability of stream patterns.

If, in fact, the slope of the valley floor of a river varies due to the sediment contribution from tributaries or due to variations in deposition during the geologic past, then the river should reflect these changes of valley slope by changes in pattern. A comparison of the experimental results with Mississippi River patterns was made possible by data obtained from the Vicksburg District, Corps of Engineers. These data show that variations in channel pattern of the Mississippi River are related to changes of the slope of the valley floor (Fig. 4). Variations in valley slope reflect the geologic history of the river, and if today the valley slope exceeds a geomorphic threshold the river will show a dramatic change of pattern.

When the valley slope is near a threshold, major flood events will significantly alter the stream pattern. This conclusion has bearing on the work of Wolman and Miller (1960), concerning the geomorphic importance of events of high magnitude. They concluded that, although a major amount of work is done by events of moderate magnitude and relative frequent occurrence, nevertheless, the large storm or flood may have a major role in landscape modification. However, evidence on the influence of rare and large events on the landscape is equivocal. Major floods have destroyed the flood plain of Cimarron River (Schumm and Lichty, 1963), but equally large events have not significantly affected the Connecticut River (Wolman and Eiler, 1958).

These and other observations indicate that a major event may be of major or minor importance in landscape modification, and an explanation of the conflicting evidence requires further consideration of the threshold

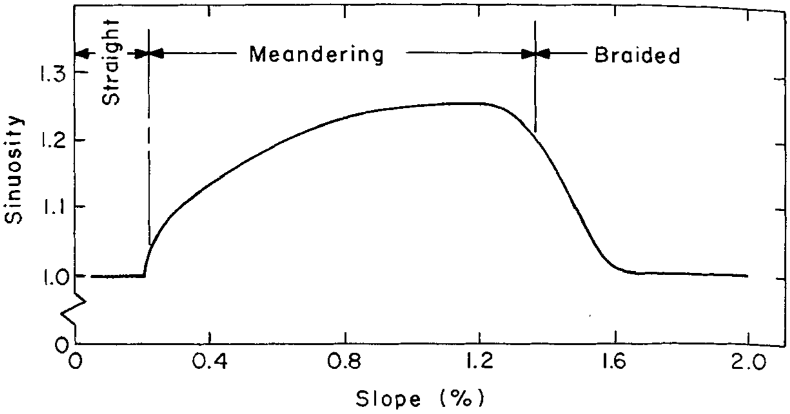

Figure 3. Relation between valley slope and sinuosity (ratio of channel length to length of flume or length of valley) during experiments. The change from a straight to a sinuous pattern, and from a sinuous to a braided pattern occurs at two threshold slopes. The absolute value of slope at which such changes occur will be influenced by discharge. Discharge was maintained at 0.15 cfs during the experiments. (After Schumm, S. A. and Khan, H. R., 1972.)

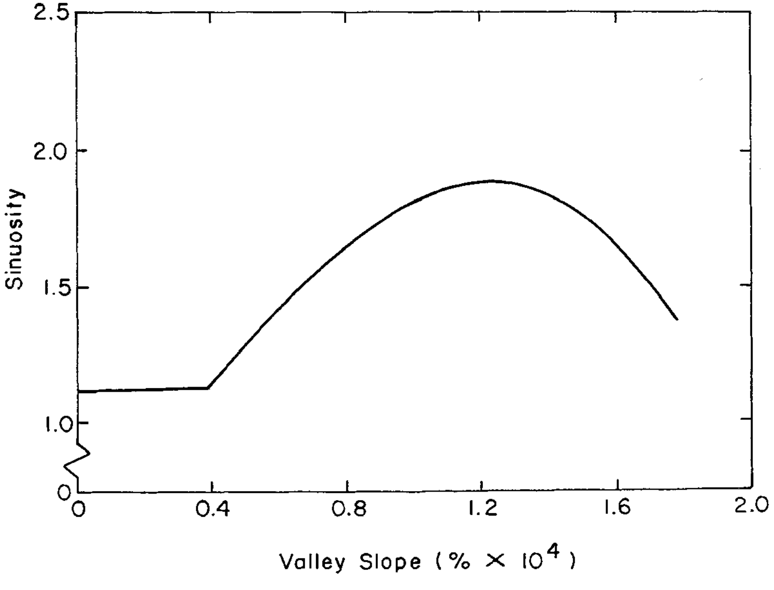

Figure 4. Relation between valley slope and sinuosity between Mississippi River between Cairo, Illinois and Head of Passes, Louisiana. Data from Potamology Section, U. S. Army Corps of Engineers, Vicksburg, Mississippi. Scatter about curve reflects natural variation of sinuosity. (After Schumm, et al., 1972)

concept. Some landscapes or components of a landscape have apparently evolved to a condition of geomorphic instability and these landforms fail; that is, depending on their development, they will be significantly modified by a large infrequent event whereas others will be unaffected. Therefore, there will be, even within the same region, different responses to the same conditions of stress.

When within a landscape some conponents fail by erosion whereas others do not, it is clear that erosional thresholds have been exceeded locally. One of the most significant problems of the geomorphologist or land manger is the location of incipiently unstable components of a landscape. The recognition of geomorphic thresholds within a given region will be a significant contribution to both an understanding of the details of regional morphology as well as providing criteria for identification of unstable land forms. At least one location, Piceance Creek basin, such a threshold has been identified. It remains to be seen how successful the concept can be applied elsewhere. It is very possible that major geomorphic thresholds associated with alluvial deposits will be identified most readily in subhumid, semiarid and arid regions, where the stabilizing influence of vegetation is least effective. However, slope stability and river pattern thresholds will exist in humid and tropical regions.

COMPLEX RESPONSE OF GEOMORPHIC SYSTEMS

Geomorphic histories tend to be complicated, and considering the climatic changes of the past few million years of earth history, one would expect them to be so. For example, throughout the world, geologists and archaeologists have studied the details of the most recent erosional and depositional history of valleys. This consists of identifying the sequence in which alluvial deposits were emplaced and then eroded. Because of worldwide climate changes during the Quaternary, it is reasonable to assume that alluvial chronologies applicable to large regions can be established. That is, a particular alluvial layer should be identifiable regionally and correlations of these deposits over large areas can then be made. There is no question that major climatic changes have affected erosional and depositional events, but when the alluvial chronologies of the last 10 to 15 thousand years are examined, it is not convincing that each event was in response to one simultaneous external change. In fact, investigations in southwestern United States reveal that during the last 10,000 years the number, magnitude and duration of erosional and depositional events in the valleys of this region not only varied from valley to valley but also varied within the same valley. For example, Kottlowski, Cooley, and Ruhe (1965) describe the situation as follows:

> "Late recent time is represented by epicycles of erosion and alluviation in the canyons and valleys of the southwest; however, the number, magnitude, and duration of the events differ from basin to basin and along reaches of the same stream."

This situation is so complex that correlations of terrace surfaces and alluvial fills over large areas seem impossible, but in the search for order, correlations are made. Haynes (1968) summarized the results of extensive radiocarbon dating of alluvial deposits in southwestern United States. His data demonstrate that, during the last 5000 years of record, there is significant temporal overlap among the three most recent alluvial deposits. This indicates that deposition was not in phase everywhere and that apparently deposition did not occur in response to a single event. Part of the complexity, at least, as related to the most recent events, may be explained by the threshold concept with erosion occurring, as described for the Piceance Creek area, when a geomorphic threshold is exceeded. However, within one region not all valleys will achieve the threshold at the same time.

There is, in addition, another explanation. We know very little about the response of a drainage system to rejuvenation. Climatic change, uplift, or lowering of baselevel can cause incision of a channel. This incision will convert the flood plain to a terrace, the geomorphic evidence of an erosional episode. However, a drainage system is composed

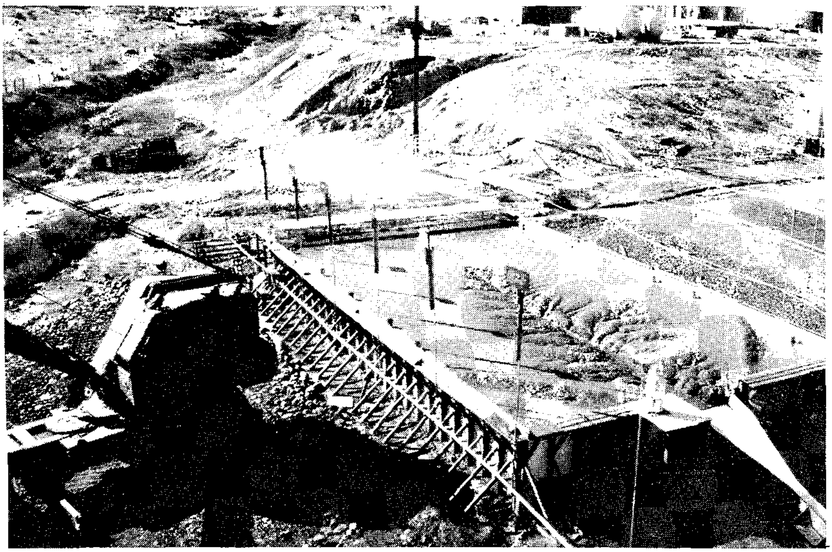

Figure 5. Drainage evolution research facility at Colorado State University. Simulated storms can be generated by a sprinkler system over the 9 x 15 m container, and the erosional development of small drainage systems can be studied.

of channels, hillsides, divides, flood plains, and terraces; it is complex. The response of this complex system to change will also be complex. That this is true was demonstrated during an experimental study of drainage system evolution at Colorado State University (Schumm and Parker, 1973).

During experimentation, a small drainage system (Fig. 5) was rejuvenated by a slight (10 cm) change of base level. As anticipated, base-level lowering caused incision of the main channel and development of a terrace (Fig. 6a,b). Incision occurred first at the mouth of the system, and then progressively upstream, successively rejuvenating tributaries and scouring the alluvium previously deposited in the valley (Fig. 6b). As erosion progressed upstream, the main channel became a conveyor of upstream sediment in increasing quantities, and the inevitable result was that aggradation occurred in the newly cut channel (Fig. 6c). However, as the tributaries eventually became adjusted to the new baselevels, sediment loads decreased, and a new phase of channel erosion occurred (Fig. 6d). Thus, initial channel incision and terrace formation was followed by deposition of an alluvial fill, channel braiding, and lateral erosion, and then, as the drainage system achieved stability, renewed incision formed a low alluvial terrace. This low surface formed as a result of the decreased sediment loads when the braided channel was converted into a better-defined channel of lower width-depth ratio. The low surface was not a flood plain because it was not flooded at maximum discharge.

Somewhat similar results were obtained by Lewis (1949) in a pioneering experiment performed in a small wooden trough four m. long and 50 cm wide. Lewis cut a simple drainage pattern in sediment (four parts sand, one part mud). He then introduced water at the head of the flume into both the main channel and into two tributaries. The main channel debouched onto a "flood plain" before entering the "sea" (tail box of flume).

During the experiment, the break in slope or knickpoint at the upstream edge of the "flood plain" eroded back, rejuvenating the upstream drainage system. Initially, erosion in the head waters was rapid as the channels adjusted, and deposition occurred on the "flood plain," thereby increasing its slope. As the upstream gradients were decreased by erosion and the stream courses stabilized, sediment supply to the "flood plain" decreased. Because of the reduction of the sediment load the stream cut into the alluvial deposits in the upper part of the flood plain to form a terrace. Lewis concludes that "perhaps the most significant fact revealed by the...experiment is that terraces were built in the lower reaches without any corresponding change of sea levels, tilt or discharge." From our results and those of Lewis, it seems that an event causing an erosional response within a drainage basin (tilting, changes of base level, climate and/or land use) automatically creates a negative feedback (high sediment production) which results in deposition; this is eventually followed by incision of alluvial deposits as sediment loads decrease.

A similar sequence of events may be under way in Rio Puerco, a major arroyo in New Mexico, as well as in other Southwestern channels. For example, the dry channel of Rio Puerco, although previously trenched to depths of 13 m, is now less than four m deep near its mouth. This is due to deposition caused by very high sediment loads produced by the rejuvenated drainage system.

Within a complex natural system, one event can trigger a complex reaction (morphologic and/or stratigraphic) as the components of the system respond progressively to change. This principle provides an explanation of the complexities of the alluvial chronologies, and it suggests that an infrequent event, although performing little of the total work within a drainage system, may, in fact be the catalyst that causes the crossing of a geomorphic threshold and the triggering of a complex sequence of events that will produce significant landscape modification.

CONCLUSIONS

Although we continually speak and write about the complexity of geomorphic systems, nevertheless, we constantly simplify in order to understand these systems. The experimental studies discussed in this

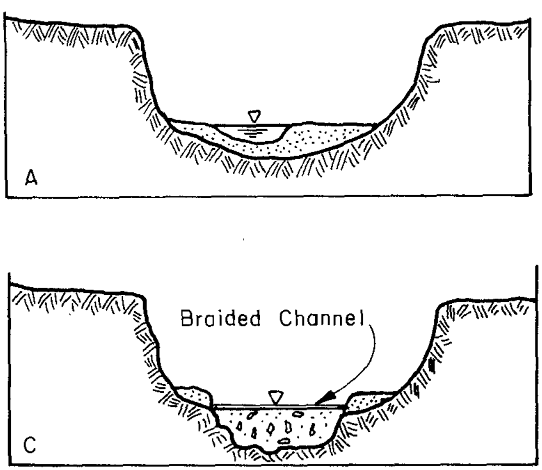

Figure 6. Diagrammatic cross sections of experimental channel 1.5 m from outlet of drainage system (base level) showing response of channel to one lowering of base level.

A. Valley and alluvium, which was deposited during previous run, before base level lowering. The low width-depth channel flows on alluvium.

B. After base level lowering of 10 cm, channel incises into alluvium and bedrock floor of valley to form a terrace. Following incision, bank erosion widens channel and partially destroys terrace (Figure 2C).

C. An inset alluvial fill is deposited, as the sediment discharge from upstream increases. The high width-depth ratio channel is braided and unstable.

D. A second terrace is formed as the channel incises slightly and assumes a low width-depth ratio in response to reduced sediment load. With time, in nature, channel migration will destroy part of the lower terrace, and a flood plain will form at a lower level.

paper are good examples of this approach. Simplification and the search for order in simplicity caused instrinsic thresholds to be overlooked in preference to explanations based on external controls. For example, the explanation of the details of the Holocene record and the distribution of modern erosion and depositional features in the western United States may well depend on our understanding of thresholds and complex response. These concepts do not conflict with the cycle of erosion or with the concept of dynamic equilibrium; rather, they supplement them.

It need not be true that landscape discontinuities or what appear to be abrupt changes in the erosional evolution of drainage systems must always be related to external influences. The evolution of land forms, at least in semiarid and arid regions, need not be progressive in the sense of constant and orderly development; in fact, change may occur both progressively and by saltation; that is, by jumps from one dynamic equilibrium to a new one. Obviously, hydrologic and meteorological events are discontinuous (Tricart, 1962) but even if they occur at a constant rate, changes in the geomorphic system itself (changing landform morphology and sediment loads) will cause abrupt adjustments of the system due to the existence of intrinsic thresholds.

It is very possible that, without the influence of external variables and over long time spans progressive erosion reduction of a landscape will be interrupted by periods of rapid readjustment, as geomorphic thresholds are exceeded. Readjustment of the system will be complex as morphology and sediment yields change with time. The timing of these changes unquestionably will be related to major flood or storm events, but such events, as emphasized earlier, may be only the catalyst that induces the change at a particular time. That is, it is the existence of geomorphic thresholds, and the complex feedback response of geomorphic systems, that permit high magnitude events to play a major role in landscape evolution.

Newtonian physical principles are utilized by engineers to control the landscape and by geomorphologists to attempt an explanation for the inception, evolution, and character of geomorphic systems. These physical laws apply to natural geomorphic situations, but their predictive power is reduced by the complexity of the field situation. For example, an increase in gravitational forces would probably not everywhere cause an equal acceleration in erosional rates. That is, increasing stress may not produce commensurate strain, but local failures will occur. Thus, the application of stress over time will not everywhere have the same result especially as the system to which stress is applied is itself changing through time. The logical consequence of the above situation as outlined in this paper is that high magnitude events will not everywhere produce dramatic erosional events; rather the result depends on the character of the geomorphic system.

The importance of this approach to the investigation of landforms is in its potential for application to prediction of landform response to both natural and man-induced change. The fact that, at least locally, geomorphic thresholds of instability can be defined quantitatively indicates that they can be identified elsewhere and then used as a basis for recognition of potentially unstable landforms in the field. This approach provides a basis for preventive erosion control. Using geomorphic principles the land manager can spend his limited funds in order to prevent erosion rather than spending it in a piecemeal fashion to attempt to restore seriously eroding areas to their natural conditions.

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