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TIME, SPACE, AND CAUSALITY IN GEOMORPHOLOGY[1]

TEMPO, ESPAÇO E CAUSALIDADE EM GEOMORFOLOGIA

TEMPS, ESPACE ET CAUSALITÉ EN GÉOMORPHOLOGIE

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ABSTRACT
The distinction between cause and effect in the development of landforms is a function of time and space (area) because the factors that determine the character of landforms can be either dependent or independent variables as the limits of time and space change. During moderately long periods of time, for example, river channel morphology is dependent on the geologic and climatic environment, but during a shorter span of time, channel morphology is an independent variable influencing the hydraulics of the channel.

During a long period of time a drainage system or its components can be considered as an open system which is progressively losing potential energy and mass (erosion cycle), but over shorter spans of time self-regulation is important, and components of the system may be graded or in dynamic equilibrium. During an even shorter time span a steady state may ex1st. Therefore, depending on the temporal and spacial dimensions of the system under consideration, landforms can be considered as either a stage in a cycle of erosion or as a system in dynamic equilibrium.

INTRODUCTION

Current emphasis on the operation of erosion processes and their effects on landforms (Strahler, 1950, 1952) not only has opened the way to new avenues of research but also introduces the possibility of misunderstanding the role of time in geomorphic systems. As Von Bertalanffy (1952, p. 109) put it, “In physical systems events are, in general, determined by the momentary conditions only. For example, for a falling body, it does not matter how it has arrived at its momentary position, for a chemical reaction it does not matter in what way the reacting compounds were produced. The past is, so to speak, effaced in physical systems. ln contrast to this, organisms appear to be historical beings”. From this point of view, although landforms are physical systems and can be studied for the information they afford during the present moment of geologic time, they are also analogous to organisms because they are systems influenced by history. Therefore, a study of process must attempt to relate causality to the evolution of the system.

It is the purpose of this discussion to demonstrate the importance of both time and space (area) to the study of geomorphic systems. We believe that distinctions between cause and effect in the molding of landforms depend on the span of time involved and on the size of the geomorphic system under consideration. Indeed, as the dimensions of time and space change, cause-effect relationships may be obscured or even reversed, and the system itself may be described differently.

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TIME, SPACE, AND THE FLUVIAL CYCLE OF EROSION

The description of the changes occurring in a landscape with time, according to the cycle of erosion as propounded by Davis, is encountered less frequently in current geomorphic writings. ln the study of geomorphic processes earth scientists are applying themselves to modem problems, and the spatial-temporal range of their research is considerably curtailed. This is necessary if the knowledge of processes is to be developed; however, even in this work the historical aspect of landscape evolution or the time dimension should not be neglected. The neglect of time leads to confusion and needless controversy. For example, recent papers by Hack (1960) and Chorley (1962) may startle some geomorphologists by the rejection of the time dimension, which is a major concern of the geologist. The discussion that follows is an at· tempt to show that what Hack and Chorley suggest need not be a break with tradition but is simply a method of considering the landscape within narrow temporal limits.

Hack (1960, p. 85) suggests that many elements of the landscape are in dynamic equilibrium with the processes acting upon them; that is, “The forms and processes are in a steady state of balance and may be considered as time independent”. He compares this condition with that of a soil undergoing erosion at the surface at the same rate as the lower boundaries of the soil horizons move downward into the regolith (Nikiforoff, 1959). Hack (1960, p. 94) continues his argument as follows: “The theory of dynamic equilibrium explains topographic forms and the differences between them in a manner that may be said to be independent of time. The theory is concerned with the relations between rocks and processes as they exist in space. The forms can change only as the energy applied to the system changes”.

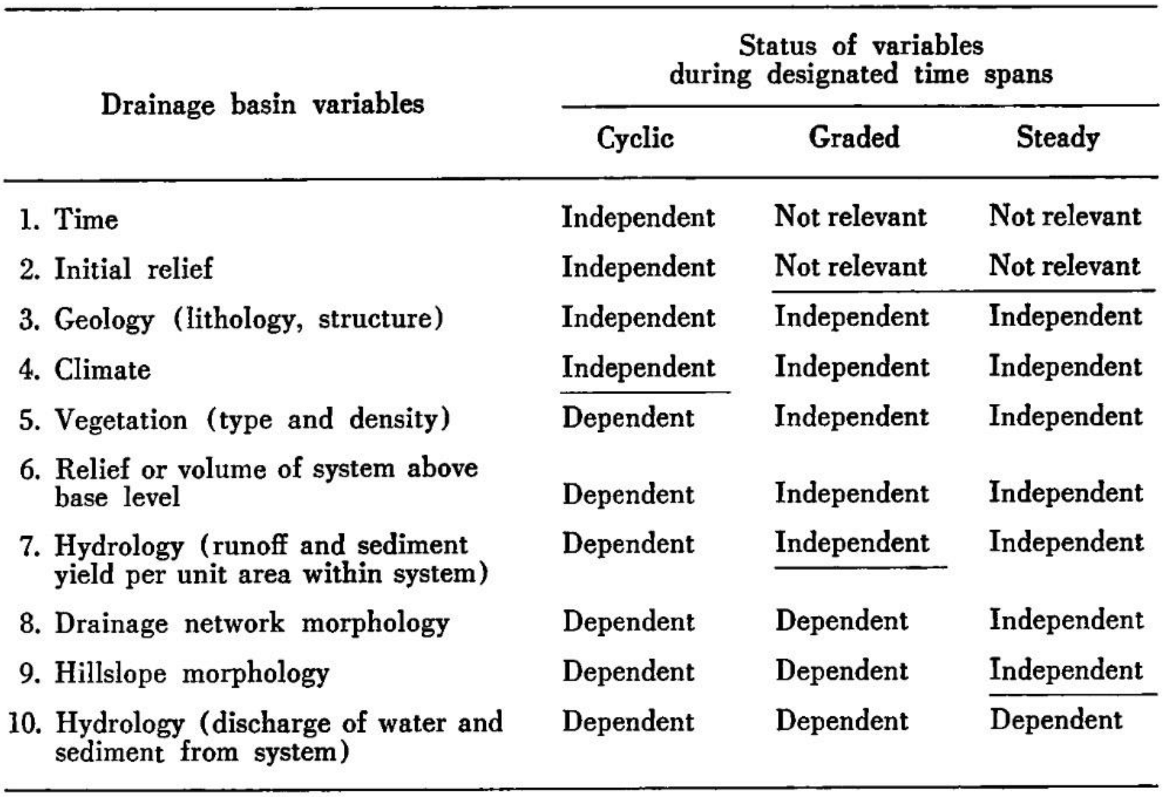
This concept is synonymous to that of the physical system described by Von Bertalanffy in which, “The past is, so to speak, effaced”. Nevertheless, after excluding time from his system, Hack considers it in the following qualification, “It is obvious, however, that erosional energy changes through time and hence forms must change". A change of erosional energy can be initiated by many factors, of which diastrophism or climate change are the most obvious. ln addition. with the passage of time erosional modification of the landforms themselves will affect erosional energy. Therefore, it appears impossible to exclude time and history from a consideration of landforms except during the study of purely empirical relations among variables, which may or may not reflect causality.

Chorley likewise feels that freedom from the historical approach is desirable, because research efforts are then directed toward a study of the rate and manner of operation of erosional processes, the empirical relations that exist between a landscape and its components, and the relations between the erosion processes and the landform. Chorley (1962, p. 3) illustrates the difficulty of reconciling the two approaches, the Davisian cycle of erosion and dynamic equilibrium, as follows: “ln the former, the useful concept of dynamic equilibrium or grade rests most uncomfortably; in the latter… the progressive loss of a component of potential energy due to relief reduction imposes an un- welcome historical parameter”.

To resolve the controversy resulting from these two viewpoints it may be necessary to think only in terms of large and small areas or of long and short spans of time. A choice must be made whether only components of a landscape are to be considered or whether the system is to be considered as a whole. Also, a choice must be made as to whether the relations between landforms and modern erosion processes are to be considered or whether the origin and subsequent erosional history of the system is to be considered. ln table 1 an attempt is made, using a hypothetical drainage basin as an example, to demonstrate that the concepts of cyclic erosion with time and timeless dynamic equilibrium are not mutually exclusive.

The variables listed in table 1 are arranged in a hierarchy we believe approximates the increasing degrees of dependence of the variables considered. For example, time, initial relief, geology, and climate are obviously the dominant independent variables that influence the cycle of erosion. Vegetational type and density depend on lithology and climate. As time passes the relief of the drainage system or mass remaining above base level is determined by the factors above it in the table, and it, in turn, strongly influences the runoff and sediment yield per unit area within the drainage basin. The runoff and sediment yield within the system establish the characteristic drainage network morphology (drainage density, channel shape, gradient, and pattern) and hillslope morphology (angle of inclination and profile form) within the constraints of relief, climate, lithology, and time. The morphologic variables, in turn, strong1y influence the volumes of runoff and sediment yield which leave the system as water and sediment discharge.

Table 1 - The status of drainage basin variables during time spans of decreasing duration.



Drainage basin variables	Status of variables during designated time spans		
	Cyclic	Graded	Steady
1. Time	Independent	Not relevant	Not relevant
2. Initial relief	Independent	Not relevant	Not relevant
3. Geology (lithology, structure)	Independent	Independent	Independent
4. Climate	Independent	Independent	Independent
5. Vegetation (type and density)	Dependent	Independent	Independent
6. Relief or volume of system above base level	Dependent	Independent	Independent
7. Hydrology (runoff and sediment yield per unit area within system)	Dependent	Independent	Independent
8. Drainage network morphology	Dependent	Dependent	Independent
9. Hillslope morphology	Dependent	Dependent	Independent
10. Hydrology (discharge of water and sediment from system)	Dependent	Dependent	Dependent

Among the variables listed on table 1, every cause appears to be an effect a cause (Mackin, 1963, p. 149); therefore, it is necessary to set limits to the system that is considered. Obviously neither the causes of geology, climate, and initial relief nor the effects of water and sediments discharge concern us here.

The three major divisions of table 1 are time spans which are termed cyclic, graded, and steady. The absolute length of these time spans is not important. Rather, the significant concept is that the system and its variables may be considered in relation to time spans of different duration.

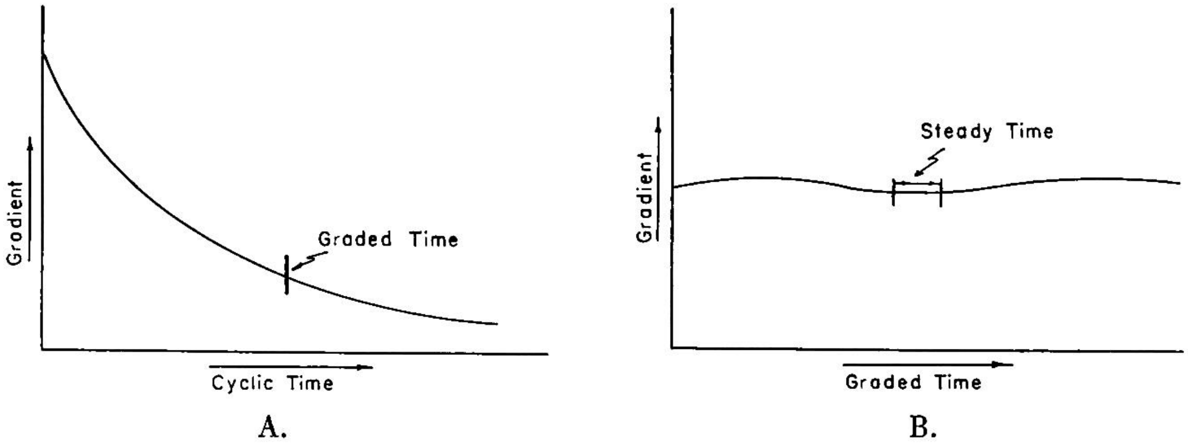
Cyclic time, of course, represents a long span of time. It might better be referred to as geologic time, but in order to keep the terminology of the table consistent, cyclic is used because it refers to a time span encompassing an erosion cycle. Cyclic time would extend from the present back in time to the beginning of an erosion cycle.

Consider a landscape that has been tectonically stable for a long time. A certain potential energy exists in the system because of relief, and energy enters the system through the agency of climate. Over the long span of cyclic time a continual removal of material (that is, expenditure of potential energy) occurs and the characteristics of the system change. A fluvial system when viewed from this perspective is an open system undergoing continued change and there are no specific or constant relations between the dependent and independent variables as they change with time (fig. 1a).

During this time span only time, geology, initial relief, an el climate are independent variables. Time itself is perhaps the most important independent variable of a cyclic time span. It is simply the passage of time since the beginning of the erosion cycle, but it determines the accomplishments of the erosional agents and, therefore, the progressive changes in the morphology of the system. Vegetational type and density are largely dependent on climate and lithology, but they significantly influence the hydrology and erosional history of a drainage basin. If all the independent variables are constant except time, then as time passes the average relief and mass volume of material remaining with in the drainage system, will decrease. As the relief or mass of the system changes so will the other dependent morphologic and hydrologic variables.

Figure 1 - Diagrams illustrating the time spans of table 1. Channel gradient is used as the dependent variable in these examples.

a. Progressive reduction of channel gradient du ring cyclic time. During graded time, a small fraction of cyclic time, the gradient remains relatively constant.
b. Fluctuations of gradient above and below a mean during graded time. Gradient is constant during the brief span of steady time.



With regard to space or the area considered, it is possible to consider an entire drainage system or any of its component parts during a cyclic time span. For example, the reduction of an entire drainage system or only the decrease in gradient of a single stream may be considered (fig. 1a) during cyclic time.

The graded time span (table 1) refers to a short span of cyclic time during which a graded condition or dynamic equilibrium exists. That is, the landforms have reached a dynamic equilibrium with respect to processes acting on them. When viewed from this perspective one sees a continual adjustment between elements of the system, for events occur in which negative feedback (self-regulation) dominates. ln other words the progressive change during cyclic time is seen to be, during a shorter span of time, a series of fluctuations about or approaches to a steady state (fig. 1b). This time division is analogous to the “period of years” used by Mackin (1948, p. 470) in his definition of a graded stream by which he rules out seasonal and other short-term fluctuations, as well as the slow changes that accompany the erosion cycle.

As an erosion cycle progresses, more and more of the landscape may approach dynamic equilibrium. That is, the proportion of graded landforms may increase, and it seems like1y that temporary graded conditions become more frequent as time goes on. However, it is apparent that during this time span the graded condition can apply only to components of the drainage basin. The entire system cannot be graded because of the progressive reduction of relief or volume of the system above base level, which occurs through export of sediment from the system. A hil1slope profile or river reach, however, may be graded. Therefore, unlike cyclic time when no restriction was placed on space or area considered, graded time is restricted to components of the systems or to smaller areas.

During a graded time span, the status of some of the variables listed on table 1 changes. For example, time has been eliminated as an independent variable, for although the system as a whole may be undergoing a progressive change of very small magnitude, some of the components of the system will show no progressive change (that is, graded streams and hillslopes}. Initial relief also has no significance because the landform components are considered with respect to their climatic, hydrologic, and geologic environment (Hack, 1960), and initial relief with time has been designated as not relevant on table 1.

In addition, some of the variables that are dependent during a long period of progressive erosion become independent during the shorter span of graded time. The newly independent hydrologic variables, runoff and sediment yield. are especially important because during a graded time span they take on a statistical significance and define the specific character of the drainage channels and hillslopes, whereas during a cyclic time span there is a progressive change in these morphologic variables.

The geomorphic variables of hillslope and drainage network morphology of graded time may be considered as “time-independent” in the meaning of Hack (1963, written communication). That is, relict features may not he present, and the landforms may he explained with regard to the independent variables without regard to time.

During a steady time span (table 1) a true steady state may exist in contrast to the dynamic equilibria of graded time (fig. 1b). These brief periods of time are referred to as a steady time span because in hydraulics steady flow occurs when none of the variables involved at a section change with time. The landforms, during this time span, are truly time independent because they do not change, and time and initial relief have again been eliminated as independent variables. During this time span only water and sediment discharge from the system are dependent variables.

Obviously the steady state condition is not applicable to the entire drainage basin. Although an entire drainage basin cannot be considered to be in a steady state over even the shortest time span, yet certain components of the basin may he. For example, a stream over short reaches may export as much water and sediment as introduced into the reach, yet the river as a whole is reducing its gradient in the headwaters (cyclic erosion). ln addition, the entire drainage basin may be losing relief as hillslopes are lowered (cyclic erosion); however, segments of the hillslopes may remain at the same angle of inclination and act as slopes of transportation (steady state) or they may retreat parallel, maintaining their form (dynamic equilibrium), but the volume of the drainage basin is being reduced nevertheless. Thus over short periods of time and in small areas the steady state may be maintained. Over large areas progressive reduction of the system occurs, and this is true over long periods of time.

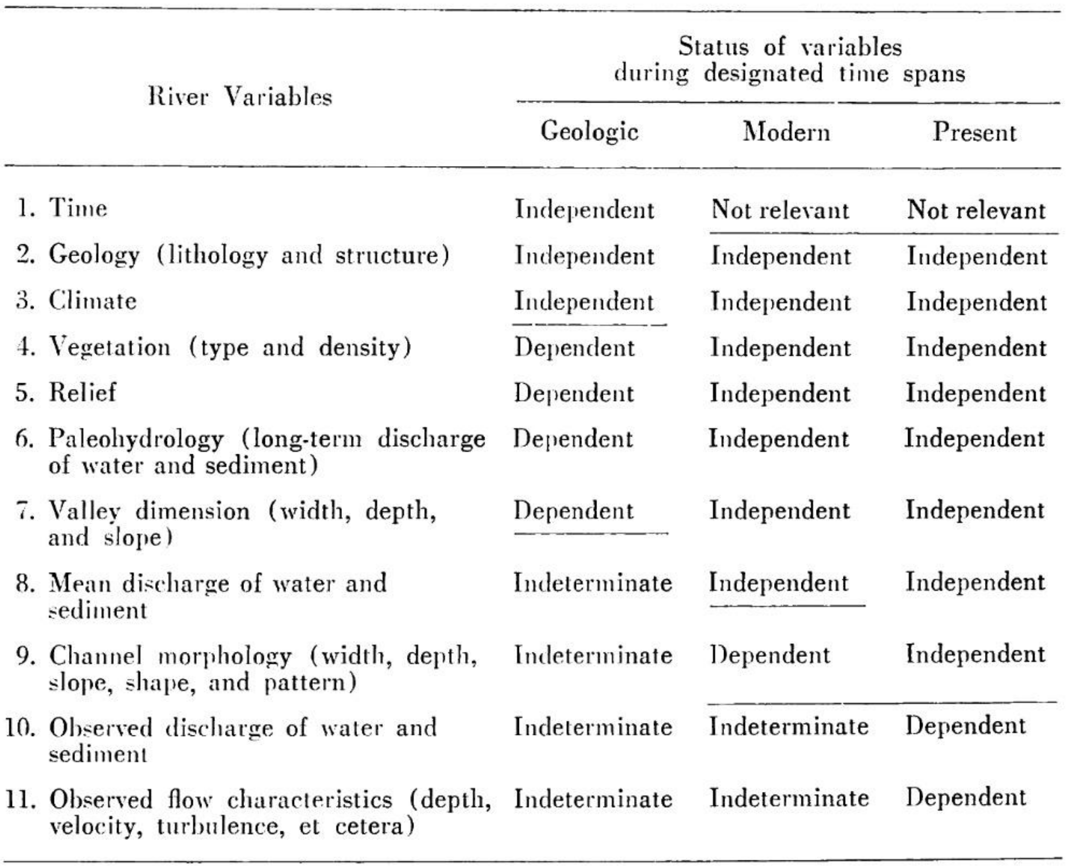
The preceding discussion and the relations presented in table 1and figure 1 have the sole object of demonstrating that, depending on the time span in· volved, time may be either an extremely important independent variable or of relatively little significance to a study of landforms.

FLUVIAL MORPHOLOGY ANO HYDRAULICS

In this section a specific example of river channel morphology and hydraulics will be cited to illustrate how, as time spans are shortened, there is a shift from dependence to independence among the variables and how, during the shortest span of time, an apparent reversal of cause and effect may occur.

In table 2 an attempt has been made to illustrate the effect of time span on the interrelations between dependent and independent variables of a river system. A similar table has been presented by Kennedy and Brooks (in press) to compare independent and dependent variables in the flume and field situations. As in the preceding discussion, it is the time span or duration of a time period that is important, but Pleistocene and Recent geomorphic history is such that in many areas it is possible to divide the time involved into three spans, termed geologic, modem, and present, each shorter and more recent than the span that precedes it.

Table 2 - The status of river variables du ring time spans of decreasing duration.



River Variables	Status of variables during designated time spans		
	Geologic	Modern	Present
1. Time	Independent	Not relevant	Not relevant
2. Geology (lithology and structure)	Independent	Independent	Independent
3. Climate	Independent	Independent	Independent
4. Vegetation (type and density)	Dependent	Independent	Independent
5. Relief	Dependent	Independent	Independent
6. Paleohydrology (long-term discharge of water and sediment)	Dependent	Independent	Independent
7. Valley dimension (width, depth, and slope)	Dependent	Independent	Independent
8. Mean discharge of water and sediment	Indeterminate	Independent	Independent
9. Channel morphology (width, depth, slope, shape, and pattern)	Indeterminate	Dependent	Independent
10. Observed discharge of water and sediment	Indeterminate	Indeterminate	Dependent
11. Observed flow characteristics (depth, velocity, turbulence, et cetera)	Indeterminate	Indeterminate	Dependent

It is almost impossible to assign temporal boundaries to these time spans because their duration will vary with each example considered. Nevertheless, geologic time in this sense begins during the Pleistocene Epoch, because it is during the higher discharges of the glacial stages that the width and depth of many valleys were established (Dury, 1962). Since the Pleistocene there undoubtedly have been som1 modifications of these valleys hut their major characteristics were determined both by the higher discharge of the Pleistocene and the post-Pleistocene adjustments to a changed hydrologic regimen. For this reason geologic time probably should end at perhaps 5000 or 10,000 years ago. However, to keep table 2 consistent with table 1 geologic time is defined as beginning 1,000,000 years ago and extending to the present.

During geologic time (table 2), time, geology, and climate are independent variables. Initial relief is not included because geologic time does not extend back to the origin of the system. Vegetation and relief are considered to be dependent variables, as is the paleohydrology of the system, which con- trolled the dimensions of the valley du ring geologic time. For geologic time we can know little or nothing about the dependent variables in the hierarchy below valley dimensions (table 2), and these variables are classed as indeterminate.

In the time span termed modern (table 2) (arbitrarily defined as the last 1000 years) the number of independent variables increases, and some previously indeterminate variables become measurable. For example, valley dimensions become independent during modern time because they were defined by the paleohydrology of geologic time and inherited from geologic time. The mean discharge of water and sediment during modem time is also cons1dered an independent variable, because it determines the morphology of the modem channel. Only channel morphology is dependent during modern time. Modem time is 1000 years in duration; therefore, the observed discharge and flow characteristics, which can be measured only during a brief span of time, are indeterminate.

During the short span of present time (defined as 1 year or less), channel morphology assumes an independent status because it has been inherited from modem time. The present or observed discharge of water and sediment and flow characteristics can be measured at any moment during present time, and these variables are no longer indeterminate.

It is du ring the brief span of present time that the possibility of an apparent reversal of cause and effect may occur, due to feedback from the dependent to the independent variables. For example. a major flood during this brief span of time might so alter the flow characteristics that a modification of channel dimensions and shape could occur. Just as water depth and velocity can be adjusted in a flume to modify sediment transport, so there is a feedback from flow velocity to sediment discharge and channel morphology. That is, as discharge momentarily increases, sediment that was previously stationary on the channel floor may be set in motion. The resulting scour, albeit minor, will influence channel depth. gradient, and shape. Thus, short term changes in velocity can cause modification of some of the independent variables.

These modifications are usually brief and temporary, and the mean values of channel dimensions and sediment discharge are not permanently affected. Nevertheless. a temporary reversal of cause and effect can occur, which, when documented quantitatively, may be a source of confusion in the interpretation of geomorphic processes. This is best demonstrated by comparing the conflicting conclusions that could result from studying fluvial processes in the hydraulic laboratory and in a natural stream. The measured quantity of sediment transported in a flume is dependent on the velocity and depth of the flowing water and on flume shape and slope. An increase in sediment transport will result from an increase in the slope of the flume or an increased discharge. In a natural stream, however, over longer periods of time, it is apparent that mean water and sediment discharge are independent variables, which determine the morphologic characteristics of the stream and, therefore, the flow characteristics (table 2, modern time). Furthermore, over very long periods of time (geologic) the independent variables of geology, relief and climate determine the discharge of water and sediment with all other morphologic and hydraulic variables dependent. Both Mackin (1963) and Kennedy and Brooks (in press) used this identical example to illustrate the need to consider how time spans are relevant to the explanation of fluvial phenomena.

Kennedy and Brooks (in press) state it thusly (Q and Q_s are water and sediment discharge),

> Streams are seldom if ever in a steady state (because of finite time required to change bed forms and depth) and transitory adjustments are accomplished by storage of water and sediment. Water storage is relatively short (hours and days) and occurs simply by the increasing of river stage or overbank flooding; sediment storage (+ or -) occurs by deposition or scour. Thus for the short term, Q_s may be considered a dependent variable, with departures of the sediment inflow from the equilibrium transport rate being absorbed in temporary storage (for months or years). But in the long term the river must assume a profile and other characteristics for which on the average the inflow of water and sediment equals the outflow; consequently for this case (called a “graded” stream by geologists), Q and Q_s are… independent variables.

Table 2 is more than a scholarly exercise in sorting variables, for although, as our knowledge increases, it will require modification, it can be of immediate use in the consideration of problems of fluvial morphology. For example, assuming we have arranged the variables in correct order, if flow characteristics are dependent variables for a modem river then currents or the helicoidal flow measured at river bends should not be the cause of meanders. ln other words, sinuosity of the river (the ratio of valley slope to channel gradient) influences the flow character not the converse. Specifically, helicoidal flow exists because of a meander, which in tum may exist partly because of past conditions of flow (paleohydrology).

As another example, in a set of data collected for Great Plains rivers it was found that a highly significant correlation exists between valley slope and stream gradient. At first, this appears trivial for slope is correlated with slope. However, if table 2 is correct, the slope of modem valleys is an independent variable dependent on the paleohydrology of geologic time, and the existing, modem channel slope is a dependent variable.

Variations in the sinuosity of the Great Plains rivers have been explained (Schumm, 1963) by the decrease in post-Pleistocene discharge and a change in the amount and type of sediment transported by the rivers. Depending on the changes in sediment load and discharge, the present stream may require a slope identical with the valley slope (sinuosity is 1) or much less than the valley slope (sinuosity is greater than 1 but usually less than 2.5). The valley floor, therefore, is the surface upon which the present river flows, and depending on changes in sediment and discharge, the river may flow at the slope of the valley or at a slope considerably less. Valley slope, as indicated on table 1, is an independent variable exerting a control on stream gradient.

CONCLUSIONS

The distinction of cause and effect among geomorphic variables varies with the size of a landscape and with time. Landscapes can be considered either as a whole or in terms of their components, or they can be considered either as a result of past events or as a result of modem erosive agents. Depending on one's viewpoint the landform is one stage in a cycle of erosion or a feature in dynamic equilibrium with the forces operative. These views are not mutually exclusive. It is just that the more specific we become the shorter is the time span with which we deal and the smaller is the space we can consider. Conversely when dealing with geologic time we generalize. The steady state concept can fit into the cycle of erosion when it is realized that steady states can be maintained only for fractions of the total time involved.

The time span considered also influences causality as the sets of independent and dependent variables of tables 1 and 2 show. If the variables were not considered with respect to the time span involved, in many cases it would be difficult to determine which variables are independent. Mackin's (1963) and Kennedy and Brooks' (in press) suggestions forestall any arguments between workers in the laboratory and workers in the field. ln the same manner the disparate points of view of the historically oriented geomorphologist and the student of process can be reconciled.

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