Geomorphology and General Systems Theory

GEOLOGICAL SURVEY PROFESSIONAL PAPER 500-B

Chorley—GEOMORPHOLOGY AND GENERAL SYSTEMS THEORY—Geological Survey Professional Paper 500-B

Geomorphology and General Systems Theory

By RICHARD J. CHORLEY

THEORETICAL PAPERS IN THE HYDROLOGIC AND GEOMORPHIC SCIENCES

GEOLOGICAL SURVEY PROFESSIONAL PAPER 500-B

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1962

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington 25, D.C.

CONTENTS

648952—62

GEOMORPHOLOGY AND GENERAL SYSTEMS THEORY

By Richard J. Chorley

"[Nature] * * * creates ever new forms; what exists has never existed before, what has existed returns not again—everything is new and yet always old * * *. There is an eternal life, a coming into being and a movement in her; and yet she goes not forward." (Goethe: Essay on Nature).[1]

ABSTRACT

An appreciation of the value of operating within an appropriate general systematic model has emerged from the recognition that the interpretation of a given body of information depends as much upon the character of the model adopted as upon any inherent quality of the data itself. Fluvial geomorphic phenomena are examined within the two systematic models which have been found especially useful in physics and biology—closed and open systems, for which simple analogies are given. Certain qualities of classic closed systems, namely the progressive increase in entropy, the irreversible character of operation, the importance of the initial system conditions, the absence of intermediate equilibrium states and the historical bias, permit comparisons to be made with the Davisian concept of cyclic erosion. The restrictions which were inherently imposed upon Davis' interpretation of landforms thus become more obvious. It is recognized, however, that no single theoretical model can adequately encompass the whole of a natural complex, and that the open system model is imperfect in that, while embracing the concept of grade, the progressive reduction of relief cannot be conveniently included within it. The open system characteristic of a tendency toward a steady state by self-regulation is equated with the geomorphic concepts of grade and dynamic equilibrium which were developed by Gilbert and later "dynamic" workers and, despite continued relief reduction, it is suggested that certain features of landscape geometry, as well as certain phases of landscape development, can be viewed profitably as partially or completely time-independent adjustments. In this latter respect the ratios forming the bases of the laws of morphometry, the hypsometric integral, drainage density, and valley-side slopes can be so considered. The relative values of the closed and open systematic frameworks of reference are recognized to depend upon the rapidity with which landscape features can become adjusted to changing energy flow, and a contrast is made between Schumm's (1956) essentially open system treatment of weak clay badlands and the historical approach which seems most profitable in treating the apparently ancient landscapes of the dry tropics.

Finally, seven advantages are suggested as accruing from attempts to treat landforms within an open system framework:

1. The focusing of attention on the possible relationships between form and process.
2. The recognition of the multivariate character of most geomorphic phenomena.
3. The acceptance of a more liberal view of changes of form through time than was fostered by Davisian thinking.
4. The liberalizing of attitudes toward the aims and methods of geomorphology.
5. The directing of attention to the whole landscape assemblage, rather than to the often minute elements having supposed historical significance.
6. The encouragement of geomorphic studies in those many areas where unambiguous evidence for a previous protracted erosional history is lacking.
7. The introduction into geography, via geomorphology, of the open systematic model which may prove of especial relevance to students of human geography.

GEOMORPHOLOGY AND GENERAL SYSTEMS THEORY

During the past decade several valuable attempts have been made, notably by Strahler (1950, 1952A, and 1952B), by Culling (1957, p. 259–261), and by Hack (1960, p. 81, 85–86; Hack and Goodlett, 1960), to apply general systems theory to the study of geomorphology, with a view to examining in detail the fundamental basis of the subject, its aims and its methods. They come at a time when the conventional approach is in danger of subsiding into an uncritical series of conditioned reflexes, and when the more imaginative modern work in geomorphology often seems to be sacrificing breadth of vision for focus on details. In both approaches it is a common trend for workers to be increasingly critical of operating within general frameworks of thought, particularly with the examples of the Davis and Penck geormorphic systems before them, and "classical" geomorphologists have retreated into restricted historical studies of regional form elements, whereas, similarly, quantitative workers have often

[1] Goethe, Fragment über die Natur (1781–82): Translated from Goethe's sämtliche Werke, Jubiläumsausgabe, Stuttgart and Berlin, v. 39, p. 3–4, undated.

withdrawn into restricted empirical and theoretical studies based on process.

It is wrong, however, to confuse the restrictions which are rightly associated with preconceived notions in geomorphology with the advantages of operating within an appropriate general systematic framework. The first lead to the closing of vistas and the decrease of opportunity; the second, however, may increase the scope of the study, make possible correlations and associations which would otherwise be impossible, generally liberalize the whole approach to the subject and, in addition, allow an integration into a wider general conceptual framework. Essentially, it is not possible to enter into a study of the physical world without such a fundamental basis for the investigation, and even the most qualitative approaches to the subject show very strong evidence of operations of thought within a logical general framework, albeit a framework of thought which is in a sense unconscious. Hack (1960), for example, has pointed to the essential difference between the approaches to geomorphology of Gilbert and Davis, and in this respect the fundamental value of the adoption of a suitable general framework of investigation based on general systems theory becomes readily apparent.

Following the terminology used by Von Bertalanffy (1950 and 1960), it is possible to recognize in general two separate systematic frameworks wherein one may view the natural occurrence of physical phenomena; the closed system and the open system (Strahler, 1950, p. 675–676, and 1952A, p. 934–935). Hall and Fagan (1956, p. 18) have defined a system as "* * * a set of objects together with relationships between the objects and between their attributes." In the light of this definition, it is very significant that one of the fundamental purposes of Davis' approach to landforms was to study them as an assemblage, in which the various parts might be related in an areal and a time sense, such that different systems might be compared, and the same system followed through its sequence of time changes. Closed systems are those which possess clearly defined closed boundaries, across which no import or export of materials or energy occurs (Von Bertalanffy, 1951). This view of systems immediately precludes a large number, perhaps all, of the systems with which natural scientists are concerned; and certainly most geographical systems are excluded on this basis, for boundary problems and the problems of the association between areal units and their interrelationships lie very close to the core of geographical investigations.

Another characteristic of closed systems is that, with a given amount of initial free, or potential, energy within the system, they develop toward states with maximum "entropy" (Von Bertalanffy, 1951, p. 161–162). Entropy is an expression for the degree to which energy has become unable to perform work. The increase of entropy implies a trend toward minimum free energy (Von Bertalanffy, 1956, p. 3). Hence, in a closed system there is a tendency for leveling down of existing differentiation within the system; or, according to Lord Kelvin's expression, for progressive degradation of energy into its lowest form, i.e. heat as undirected molecular movement (Von Bertalanffy, 1956, p. 4). This is expressed by the second law of thermodynamics (Denbigh, 1955) which, in its classic form, is formulated for closed systems. In such systems, therefore, the change of entropy is always positive, associated with a decrease in the amount of free energy, or, to state this another way, with a tendency toward progressive destruction of existing order or differentiation.

Thus, one can see that Davis' view of landscape development contains certain elements of closed system thinking—including, for example, the idea that uplift provides initially a given amount of potential energy and that, as degradation proceeds, the energy of the system decreases until at the stage of peneplanation there is a minimum amount of free energy as a result of the leveling down of topographic differences. The Davisian peneplain, therefore, may be considered as logically homologous to the condition of maximum entropy, general energy properties being more or less uniformly distributed throughout the system and with a potential energy approaching zero. The positive change of entropy, and connected negative change of free energy, implies the irreversibility of events within closed systems. This again bears striking similarities to the general operation of the geomorphic cycle of Davis. The belief in the sequential development of landforms, involving the progressive and irreversible evolution of almost every facet of landscape geometry, in sympathy with the reduction of relief, including valley-side slopes and drainage systems, is in accord with closed system thinking. Although "complications of the geographical cycle" can, in a sense, put the clock back, nothing was considered by Davis as capable of reversing the clock. The putting back of the clock by uplift, therefore, came to be associated with a release, or an absorption into the new closed system, of an increment of free energy, subsequently to be progressively dissipated through degradation.

Also, in closed systems there is the inherent characteristic that the initial system conditions, particularly the energy conditions, are sufficient to determine its ultimate equilibrium condition. This inevitability of closed-system thinking is very much associated with the view of geomorphic change held by Davis. Not only this, but the condition of a closed system at any particular time can be considered largely as a function of the initial system conditions and the amount of time which has subsequently elasped. Thus closed systems are eminently susceptible to study on a time, or historical, basis. This again enables one to draw striking analogies between closed-system thinking and the historical approach to landform study which was proposed by Davis.

Finally, it is recognized that closed systems can reach a state of equilibrium. Generally speaking, however, this equilibrium state is associated with the condition of maximum entropy which cannot occur until the system has run through its sequential development. In addition, it is impossible to introduce the concept of equilibrium into a closed-system framework of thought without the implication that it is associated with stationary conditions. The only feature of the cyclic system of Davis which employed the general concept of equilibrium was that of the "graded" condition of stream channels and slopes which, significantly, Davis borrowed from the work of Gilbert, who had an entirely noncyclic view of landform development (Hack, 1960, p. 81). Characteristically, the concept of grade was the one feature of Davis' synthesis which seems least well at home in the cyclic framework, for it has always proved difficult to imagine how, within a closed system context, a graded or equilibrium state could exist and yet the associated forms be susceptible to continued change—namely, downcutting or reduction.

The foregoing is not meant to imply that it is unprofitable to consider any assemblage of phenomena within a closed system framework, or, as Davis did, to overstress those aspects or phases which seem to achieve most significance with reference to the closed system model. It is important, however, to recognize the sources of partiality which result, not from any inherent quality of the data itself, but from the general systematic theory under which one is operating. In reality, no systematic model can encompass the whole of a natural complex without ceasing to be a model, and the phenomena of geomorphology present problems both when they are viewed within closed and open systematic frameworks. In the former, the useful concept of dynamic equilibrium or grade rests most uncomfortably; in the latter, as will be seen, the progressive loss of a component of potential energy due to relief reduction imposes an unwelcome historical parameter.

A simple, classic example of a closed system is represented by a mass of gas within a completely sealed and insulated container. If, initially, the gas at one end of the container is at a higher temperature than that at the other, this can be viewed as a condition of maximum segregation, maximum free energy, and, consequently, of maximum ability to perform work, should this thermal gradient be harnessed within a larger closed system. This is the state of minimum entropy. It is obvious, however, that this state of affairs is of a most transient character and that immediately an irreversible heat flow will begin toward the cooler end of the container. This will progressively decrease the segregation of mass and energy within the system, together with the available free energy and the ability of this energy to perform work, bringing about a similarly progressive increase of entropy. While the system remains closed nothing can check or hinder this inevitable leveling down of differences, which is so predictable that, knowing the initial energy conditions, the thermal conductivity of the gas and the lapse of time, one could accurately calculate the thermal state of the system at any required stage. Thus the distribution of heat energy and the heat flow within the system have a progressive and sequential history, the one becoming less segregated and the other ever-decreasing. Nor is it possible to imagine any form of equilibrium until all the gas has attained the same temperature, when the motion of the gas molecules is quite random and the static condition of maximum entropy obtains.

Open systems contrast quite strikingly with closed systems. An open system needs an energy supply for its maintenance and preservation (Reiner and Spiegelman, 1945), and is in effect maintained by a constant supply and removal of material and energy (Von Bertalanffy, 1952, p. 125). Thus, direct analogies exist between the classic open systems and drainage basins, slope elements, stream segments and all the other form-assemblages of a landscape. The concept of the open system includes closed systems, however, because the latter can be considered a special case of the former when transport of matter and energy into and from the system becomes zero (Von Bertalanffy, 1951, p. 156). An open system manifests one important property which is denied to the closed system. It may attain a "steady state" (Von Bertalanffy, 1950; and 1951, p. 156–157), wherein the import and export of energy and material are equated by means of an adjustment of the form, or geometry, of the system itself. It is more difficult to present a simple mechanical analog to illustrate completely the character and operations of an open system but it may be helpful to visualize one such system as represented by the moving body of water contained in a bowl which is being constantly filled from an overhead inflow and drained by an outflow in the bottom. If the inflow is stopped, the bowl drains and the system ceases to exist; whereas, if the inflow is stopped and the outflow is blocked, the system partakes of many of the features of a closed system. In such an arrangement, changes in the supply of mass and energy from outside lead to a self-adjustment of the system to accommodate these changes. Thus, if the inflow is increased, the water level in the basin rises, the head of water above the outflow increases, and the outflow discharge will increase until it balances the increased inflow. At this time the level of water in the bowl will again become steady.

Long ago, Gilbert recognized the importance of the application of this principle of self-adjustment to landform development:

> The tendency to equilibrium of action, or to the establishment of a dynamic equilibrium, has already been pointed out in the discussion of the principles of erosion and of sculpture, but one of its most important results has not been noticed.
>
> Of the main conditions which determine the rate of erosion, namely, the quantity of running water, vegetation, texture of rock, and declivity, only the last is reciprocally determined by rate of erosion. Declivity originates in upheaval, or in the displacement of the earth's crust by which mountains and continents are formed: but it receives its distribution in detail in accordance with the laws of erosion. Wherever by reason of change in any of the conditions the erosive agents come to have locally exceptional power, that power is steadily diminished by the reaction of the rate of erosion upon declivity. Every slope is a member of a series, receiving the water and the waste of the slope above it, and discharging its own water and waste upon the slope below. If one member of the series is eroded with exceptional rapidity, two things immediately result: first, the member above has its own level of discharge lowered, and its rate of erosion is thereby increased; and second, the member below, being clogged by an exceptional load of detritus, has its rate of erosion diminished. The acceleration above and the retardation below diminish the declivity of the member in which the disturbance originated: and as the declivity is reduced, the rate of erosion is likewise reduced.
>
> But the effect does not stop here. The disturbance that has been transferred from one member of the series to the two which adjoin it, is by then transmitted to others, and does not cease until it has reached the confines of the drainage basin. For in each basin all lines of drainage unite in a main line, and a disturbance upon any line is communicated through it to the main line and thence to every tributary. And as a member of the system may influence all the others, so each member is influenced by every other. There is an interdependence throughout the system. (Gilbert, 1880, p. 117–118).

This form-adjustment is brought about by the ability of an open system for self-regulation (Von Bertalanffy, 1952, p. 132–133). Le Châtelier's Principle (originally stated for equilibrium in closed systems) can be expanded also to include the so-called "Dynamic Equilibrium" or steady states in open systems:

> Any system in * * * equilibrium undergoes, as a result of a variation in one of the factors governing the equilibrium, a compensating change in a direction such that, had this change occurred alone it would have produced a variation of the factor considered in the opposite direction. (Prigogine and Defay, 1954, p. 262.)

A geomorphic statement of this principle has been given by Mackin (1948):

> A graded stream is one in which, over a period of years, slope is delicately adjusted to provide, with available discharge and with prevailing channel characteristics, just the velocity required for the transportation of the load supplied from the drainage basin. The graded stream is a system in equilibrium; its diagnostic characteristic is that any change in any of the controlling factors will cause a displacement of the equilibrium in a direction that will tend to absorb the effect of the change.

The cyclic adaptation of the concept of grade did not give sufficient importance to the factors, other than channel slope, which a stream system can control for itself, and in this respect Davis' ignorance of the significance of the practical experiments of Gilbert (1914) is most evident. A stream system cannot greatly control its discharge, which represents the energy and mass which is externally supplied into the open system. Neither can it completely control the amount and character of the debris supplied to it, except by its action of abrasion and sorting or as the result of the rapport which seems to exist regionally between stream-channel slope and valley-side slope (Strahler, 1950, p. 689). However, besides adjusting the general slope of its channel by erosion and deposition, a stream can very effectively and almost instantaneously control its transverse channel characteristics, together with its efficiency for the transport of water and load, by changes in depth and width of the channel. As Wolman (1955, p. 47) put it:

> The downstream curves on Brandywine Creek * * * suggest that the adjustment of channel shape may be as significant as the adjustment of the longitudinal profile. There is no way in which one could predict that the effect of a change in the independent controls would be better absorbed by a change in slope rather than by a change in the form of the cross section.

It may be, therefore, that a stream or reach may be virtually always adjusted (Hack, 1960, p. 85–86), in the sense of being graded or in a steady state, without necessarily presenting the smooth longitudinal profile considered by the advocates of the geomorphic cycle as the hallmark of the "mature graded condition." The state of grade is thus analogous to the tendency for steady-state adjustment, it is perhaps always present and, therefore, this presence cannot be employed necessarily as an historical, or stage, characteristic. It is interesting that the concept of the vegetational "climax," which has often been compared to that of grade, has passed through a somewhat similar metamorphosis. The original idea of a progressive approach to a static equilibrium of the ecological assemblage (Clements, 1916, p. 98–99) has been challenged by the open system interpretation of Whittaker (1955, p. 48), with an historical link being provided by the "individualistic concept" of Gleason (1926-27; 1927), much in the same way as Mackin's concept of grade links those of Davis and Wolman.

The forms developed, together with the mutual adjustment of internal form elements and of related systems, are dependent on the flow of material and energy in the steady state. The laws of morphometry (Chorley, 1957) express one aspect of this relationship in geomorphology. In addition, adjustment of form elements implies a law of optimum size of a system and of elements within a system (Von Bertalanffy, 1956, p. 7). This is mirrored by Gilbert's (1880, p. 134–135) symmetrical migration of divides and by Schumm's constant of channel maintenance (1956, p. 607), and is illustrated by Schumm's (1956, p. 609) contrast between basin areas of differing order.

Although a steady state is in many respects a time-independent condition, it differs from the equilibrium of closed systems. A steady state means that the aspects of form are not static and unchanging, but that they are maintained in the flow of matter and energy traversing the system. An open system will, certain conditions presupposed, develop toward a steady state and therefore undergo changes in this process. Such changes imply changes in energy conditions and, connected with these, changes in the structures during the process. The trend toward, and the development of, a steady state demands not an equation of force and resistance over the landscape, but that the forms within the landscape are so regulated that the resistance presented by the surface at any point is proportionate to the stress applied to it.

> Erosion on a slope of homogeneous material with uniform vegetative cover will be most rapid where the erosional power of the runoff is greatest. This nonuniform erosional process will in time result in a more stable slope profile which would offer a uniform resistance to erosion. (Little, 1940, p. 33.)

In this way the transport of mass and energy (i.e., water and debris) is carried on in the most economical manner. With time, landscape mass is therefore being removed and progressive changes in at least some of the absolute geometrical properties of landscape, particularly relief, are inevitable. It is wrong, however, to assume, as Davis did, that all these properties are involved necessarily in this progressive, sequential change. To return briefly to the analogy of the bowl. If the rush of water through the outflow is capable of progressively enlarging the orifice, the increasing discharge at the outflow, uncompensated at the inflow, will cause the head of water in the bowl to decrease. This loss of head will itself, however, constantly tend to compensate the increasing outflow, but, if the enlargement of the outflow orifice proceeds, this is a losing battle and an important feature of the system will be the progressive and sequential loss of head. However, not all features of this system will reflect this progressive change of head, and, for example, the structure of the flow within the bowl will remain much the same while any head of water at all remains there. The dimensionless ratios between landscape forms, similarly, seem to express the steady state condition of adjusted forms from which mass is constantly being removed. The geometrical ratios which form the basis of the laws of morphometry, and the height-area ratios involved in the dimensionless, equilibrium hypsometric integral are examples of this adjustment:

> In late mature and old stages of topography, despite the attainment of low relief, the hypsometirc curve shows no significant variations from the mature form, and a low integral results only where monadnocks remain * * *. After monadnock masses are removed, the hypsometric curve may be expected to revert to a middle position with integrals in the general range of 40 to 60 percent. (Strahler, 1952B, p. 1129–1130.)

In a drainage basin composed of homogenous material, in which no monadnocks would tend to form, it seems possible, therefore, that the dimensionless percentage volume of unconsumed mass (represented by the hypsometric integral) may achieve a time-independent value. It has been suggested, however, that the construction of the hypsometric curve may be so inherently restricted as to make the hypsometric integral insensitive to variations of an order which would be necessary to recognize such an equilibrium state (Leopold, written communication, 1961). This steady state principle has been tentatively extended by Schumm (1956, p. 616–617) to certain other aspects of drainage basin form:

> * * * the form of the typical basin at Perth Amboy changes most rapidly in the earliest stage of development. Relief and stream gradient increase rapidly to a point at which about 25 percent of the mass of the basin has been removed, then remains essentially constant. Because relief ratio [the ratio between total relief of a basin and the longest dimension of the basin parallel to the principal drainage] elsewhere has shown a close positive correlation with stream gradient, drainage density, and ground-slope angles, stage of development might be expected to have little effect on any of these values once the relief ratio has become constant.

In the steady state of landscape development, therefore, force and resistance are not equated (which would imply no absolute form change), but balanced in an areal sense, such that force may still exceed resistance and cause mass to be removed. Now, as has been pointed out, removal of mass under steady-state conditions must imply some progressive changes in certain absolute geometrical properties of a landscape, notably a decrease in average relief, but by no means all such properties need respond in this simple manner to the progressive removal of mass. The existence, for example, of the optimum magnitude principle for individual systems, or subsystems, implies that if the available energy within the system is sufficient to impose the optimum magnitude on that system, this magnitude will be maintained throughout a period of time and will not always be susceptible to a progressive, sequential change. Thus, Strahler (1950) has indicated that erosional slopes which are being forced to their maximum angle of repose by aggressive basal stream action will, of necessity, retain this maximum angle despite the progressive removal of mass with time.

Total energy is made up of interchangeable potential energy and flux, or kinetic, energy (Burton, 1939, p. 328) and even if the potential energy component decreases within an open system due to its general reduction, in other words along with a continual change in one aspect of form (i.e., relief), the residual flux energy may be of such overriding importance as to effectively maintain a steady state of operation. In practice the steady state is seldom, if ever, characterized by exact equilibrium, but simply by a tendency to attain it. This is partly due to the constant energy changes which are themselves characteristic of many open system operations, but the steady state condition of tendency toward attainment of equilibrium is a necessary prerequisite, according to Von Bertalanffy (1950, p. 23; and 1952, p. 132–33), for the system to perform work at all. Now, once a steady state has been established, the influence of the initial system conditions vanishes and, with it, the evidence for a previous history of the system (Culling, 1957, p. 261) (i.e., was our bowl full or empty at the start?). Indeed, in terms of analyzing the causes of phenomena which exhibit a marked steady-state tendency, considerations regarding previous history become not only hypothetical, but largely irrelevant. This concept contrasts strikingly with the historical view of development which is fostered by closed-system thinking. Wooldridge and Linton (1955, p. 3) have gone so far as to say that:

> Any such close comprehension of the terrain can be obtained in one way only, by tracing its evolution.

An even more extreme statement of the same philosophy has been made by Wooldridge and Goldring (1953, p. 165):

> The physical landscape, including the vegetation cover, is the record of *processes* and the whole of the evidence for its evolution is contained in the landscape itself.

The whole matter hinges on the rapidity with which landscape features become adjusted to energy flow, which may itself be susceptible to rapid changes, particularly during the rather abnormal latest geologic period of earth history. Obviously, most existing features are the product of both past and reasonably contemporary energy conditions, and the degree to which these latter conditions have gained ascendancy over the former is largely a function of the ratio between the amount of present energy application and the strength (whatever this may mean) of the landscape materials. Thus, the geometry of stream channels (Leopold and Maddock, 1953) and the morphometry of weak clay badlands (Schumm, 1956) show remarkable adjustments to contemporary processes—on whatever time level the action of these processes may be defined (Wolman and Miller, 1960)—whereas, at the other end of the energy/resistance scale, erosion surfaces cut in resistant rock and exposed to the low present energy levels associated with the erosional processes of certain areas of tropical Africa can only be understood on the basis of past conditions. Between these two extremes lies the major part of the subject matter of geomorphology including considerations of slope development, and it is here where the apparent dichotomy between the two systematic approaches to the same phenomena, termed by Bucher (1941; see also Strahler, 1952A, p. 924–925) "timebound" and "timeless," is most acute. In a related context, the problem of timebound-versus-timeless phenomena becomes especially obvious when rates of change and the ability to adjust are underestimated, as when vegetational assemblages have been correlated with the assumed stages of geomorphic history in the folded Appalachians by Braun (1950, p. 241–242) and in Brazil by Cole (1960, p. 174–177).

One can appreciate that in areas where good evidence for a previous landscape history still remains, the historical approach may be extremely productive, as exemplified by the work of Woolridge and Linton on southeastern England. However, in many (if not most) areas the condition is one of massive removal of past evidence and of tendency toward adjustment with progressively contemporaneous conditions. It is an impossibly restricted view, therefore, to imagine a universal approach to landform study being based only upon considerations of historical development.

Another characteristic of the open system is that negative entropy, or free energy, can be imported into it—because of its very nature. Therefore, the open system is not defined by the trend toward maximum entropy. Open systems thus may maintain their organization and regularity of form, in a continual exchange of their component materials. They may even develop toward higher order, heterogeneity, hierarchical differentiation and organization (Von Bertalanffy, 1952, p. 127–129). This is mirrored in geomorphology by the characteristic development of interrelated drainage forms, and goes along with a concept of progressive segregation (Von Bertalanffy, 1951, p. 148–149). This, to a minor extent, militates against the general view of adjustment previously discussed, insofar, as, with time, rates of interactions between form elements in an open system may tend to decrease. Therefore, it is quite reasonable to assume that mutual adjustments of form within geomorphic systems might be more difficult of accomplishment and delayed where the relief, through its influence over the potential energy of the system, is low rather than where there is a higher potential energy in the system.

Steady-state conditions can be interrupted by a disturbance in the energy flow or in the resistance, leading to form adjustments allowing a new steady state to be approached. These adjustments, however, do imply a consumption of energy and there is a "cost of transition" from one steady state to another (Burton, 1939, p. 334, 348). A particular geomorphic instance of this dissipation might be presented by the phenomenon of "overshooting" where active, but sporadic, processes are operating on weak materials, as instanced when the failure of steep slopes reduces them to inclinations very much below their repose angles, and by the excessive cutting and subsequent filling of alluvial channels associated with flash floods.

The dynamic equilibrium of the steady state manifests itself in a tendency toward a mean condition of unit forms, recognizable statistically, about which variations may take place over periods of time with fluctuations in the energy flow. These periods of time may in some instances be of very short duration, and the fluctuations of transverse stream profiles are measurable in the days, or even minutes, during which changes of discharge occur. These constant adjustments to new steady-state conditions may be superimposed on a general tendency for change possibly associated with the reduction of average relief through time. This general relief change, however, does not imply a sympathetic change of all the other features of landscape geometry. As has been demonstrated by Strahler (1958) and Melton (1957), for example, drainage density is controlled by a number of factors of which relief is only one. Recent work seems to be indicating that relief (naturally including considerations of average land slope) probably has only a relatively small influence over drainage density, which may be masked or negated altogether by the other more important factors (for example, rainfall intensity and surface resistance) which are not so obviously susceptible to changes with time. Denbigh, Hicks and Page (1948, p. 491) have pointed out that:

> Quite large changes of environment may take place, without the need for more than a small internal readjustment.

Horton (1945) did not believe, as did Glock (1931), that drainage density could be employed as a measure of landscape "age," and, indeed, it is not difficult to entertain the possibility that certain features of landscape geometry may be relatively unchanging, in actual dimensional magnitude as well as in dimensionless ratio, throughout long periods of erosional history.

For many landscape units, changes on either level are slow, or in some instances nonexistent. Under steady state conditions, therefore, corresponding local morphometric units will, as regards their form and magnitude, tend to crowd around a very significant mean value, imparting to a geomorphic region its aspects of uniformity. Strahler's (1950, p. 685) "law of constancy of slopes" is an expression of one phase of this adjustment. It is interesting that the general principle of the operation of a steady state condition was intuitively recognized long ago by Playfair (1802, p. 440):

> The geological system of Dr. Hutton, resembles, in many respects, that which appears to preside over the heavenly motions. In both, we perceive continual vicissitude and change, but confined within certain limits, and never departing far from a certain mean condition, which is such, that in the lapse of time, the deviations from it on one side, must become just equal to the deviations from it on the other.

Often the achievement of exact equilibrium in nature occurs only momentarily as variations about the mean take place (Mackin, 1948), and in these instances the existence of the steady state can only be recognized statistically (Strahler, 1954). In the study of landscape, the steady state condition indicated by discrete, close and recognizable statistical groupings of similar units, is characteristic of regions of uniform ratios between process and surface resistance.

Davis' view of landscape evolution was that the passage of time, of necessity, imprinted recognizable, significant and progressive changes, on every facet of landscape geometry. The recognition, however, that landscape forms represent a steady-state adjustment with respect to a multiplicity of controlling factors obliges one to take a less rigid view of the evolutionary aspects of geomorphology. When a geometrical form is controlled by a number of factors, any change of form with the passage of time is entirely dependent upon the net result of the effect of time upon those factors. Some factors are profoundly affected by the passage of time, others are not; some factors act directly (using the term in the mathematical sense) upon the form, others inversely; some factors exercise an important control over form aspects, others a less important one. Thus, if a particular geometrical feature of landscape is primarily controlled by a factor the action of which does not change greatly with time, or if the changes of factors having direct and inverse controls tend to cancel out the net effect of the changes, then the resulting variation in geometry may itself be small—perhaps insignificant.

A last important characteristic of open systems is that they are capable of behaving "equifinally"—in other words, different initial conditions can lead to similar end results (Von Bertalanffy, 1950, p. 25; and 1952, p. 143). Davisian (closed system) thinking is instinctively opposed to this view, and the immediate and facile assumption, for example, that most breaks of stream slope are only referable to a polycyclic mechanism is an illustration of the one cause–one effect mentality. The concept of equifinality accentuates the multivariate nature of most geomorphic processes and militates against the unidirectional inevitability of the closed system cyclic approach of Davis. The approach contrasts strikingly with that of Gilbert:

> Phenomena are arranged in chains of necessary sequence. In such a chain each link is the necessary consequent of that which precedes, and the necessary antecedent of that which follows * * * If we examine any link of the chain, we find it has more than one antecedent and more than one consequent * * * Antecedent and consequent relations are therefore not merely linear, but constitute a plexus; and this plexus pervades nature. (Gilbert, 1886, p. 286–287.)

To sum up, the real value of the open system approach to geomorphology is:

Firstly, that it throws the emphasis on the recognition of the adjustment, or the universal tendency toward adjustment, between form and process. Both form and process are studied, therefore, in equal measure, so avoiding the pitfall of Davis and his more recent associates of the complete ignoring of process in geomorphology:

> In a graded drainage system the steady state manifests itself in the development of certain topographic form characteristics which achieve a time-independent condition * * * Erosional and transportational processes meanwhile produce a steady flow (averaged over a period of years or tens of years) of water and waste from and through the landform system * * * Over the long span of the erosion cycle continual adjustment of the components in the steady state is required as relief lowers and available energy diminishes. The forms will likewise show a slow evolution.
>
> Applied to erosion processes and forms, the concept of the steady state in an open system focuses attention upon the relationship between dynamics and morphology. (Strahler, 1950, p. 676.)

The relation between process and form lies close to the heart of geomorphology and, in practice, the two are often so intimately linked that the problem of cause and effect may present the features of the "hen and the egg." Approach from either direction is valuable, however, for knowledge of form aids in the understanding of process, and studies of process help in the clearer perception of the significant aspects of form.

> The study of form may be descriptive merely, or it may become analytical. We begin by describing the shape of an object in the simple words of common speech: we end by defining it in the precise language of mathematics; and the one method tends to follow the other in strict scientific order and historical continuity * * * The mathematical definition of a "form" has a quality of precision which was quite lacking in our earlier stage of mere description * * * [employing means which] are so pregnant with meaning that thought itself is economized; * * *.
>
> We are apt to think of mathematical definitions as too strict and rigid for common use, but their rigour is combined with all but endless freedom * * * we reach through mathematical analysis to mathematical synthesis. We discover homologies or identities which were not obvious before, and which our description obscured rather than revealed: * * *
>
> Once more, and this is the greatest gain of all, we pass quickly and easily from the mathematical concept of form in its statical aspect to form in its dynamical relations: we rise from the conception of form to an understanding of the forces which gave rise to it; and in the representation of form and in the comparison of kindred forms, we see in the one case a diagram of forces in equilibrium, and in the other case we discern the magnitude and the direction of the forces which have sufficed to convert the one form into the other * * *.
>
> * * * Every natural phenomenon, however simple, is really composite, and every visible action and effect is a summation of countless subordinate actions. Here mathematics shows her peculiar power, to combine and generalize * * *.
>
> A large part of the neglect and suspicion of mathematical methods in * * * morphology is due * * * to an ingrained and deep-seated belief that even when we seem to discern a regular mathematical figure in an organism * * * [the form] which we so recognise merely resembles, but is never entirely explained by, its mathematical analogue; in short, that the details in which the figure differs from its mathematical prototype are more important and more interesting than the features in which it agrees; and even that the peculiar aesthetic pleasure with which we regard a living thing is somehow bound up with the departure from mathematical regularity which it manifests as a peculiar attribute of life * * *. We may be dismayed too easily my contingencies which are nothing short of irrelevant compared to the main issue; there is a *principle of negligibility* * * *.
>
> If no chain hangs in a perfect catenary and no raindrop is a perfect sphere, this is for the reason that forces and resistances other than the main one are inevitably at work * * *, but it is for the mathematician to unravel the conflicting forces which are at work together. And this process of investigation may lead us on step by step to new phenomena, as it has done in physics, where sometimes a knowledge of form leads us to the interpretation of forces, and at other times a knowledge of the forces at work guides us towards a better insight into form. (Thompson, 1942, p. 1026–1029.)

Secondly, open-system thinking directs the investigation toward the essentially multivariate character of geomorphic phenomena (Melton, 1957; Krumbein, 1959). It is of interest to note that the physical, and the resulting psychological, inability of geographers to handle successfully the simultaneous operation of a number of causes contributing to a given effect has been one of the greatest impediments to the advancement of their discipline. This inability has prompted, at worst, a unicausal determinism and, at best, an unrealistic concentration upon one or two contributing factors at the expense of others. Davis' preoccupation with "stage" in geomorphology has been paralleled, for example, by an undue emphasis on the part of some economic geographers upon the factor of "distance" in many analyses of economic location.

Thirdly, it allows a more liberal view of changes of form with time, so as to include the possibility of nonsignificant or nonprogressive changes of certain aspects of landscape form through time.

Fourthly, while not denying the value of the historical approach to landform development in those areas to which the application of this framework of study is appropriate, open-system thinking fosters a less rigid view regarding the aims and methods of geomorphology than that which appears to be held by proponents of the historical approach. It embraces naturally within its general framework the forms possessing relict facets, those indeed which form the basis for the present studies of denudation chronology, under the general category of the "inequilibrium" forms of Strahler (1952B). There is no uniquely correct method of treatment for a given body of information, and Postan (1948, p. 406) has been at pains to demonstrate the purely subjective distinction which exists between alternative explanations of phenomena on an immediately causal or generic basis, as against an historical or biographical one:

> For the frontier they draw separates not the different compartments of the universe but merely the different mental attitudes to the universe as a whole. What makes the material fact a fit object for scientific study is that men are prepared to treat it as an instance of a generic series. What makes a social phenomenon an historical event is that men ask about it individual or, so to speak, biographical questions. But there is no reason why the process should not be reversed; why we should not ask generic questions about historical events or should not write individual biographies of physical objects. Here Spinoza's argument still holds. The fall of a brick can be treated as a mere instance of the general study of falling bricks, in which case it is a material fact, and part and parcel of a scientific enquiry. But it is equally possible to conceive a special interest in a particular brick and ask why that individual brick behaved as it did at the unique moment of its fall. And the brick will then become an historical event. Newton must have been confronted with something of the same choice on the famous day when he sat under the fabulous apple tree. Had he asked himself the obvious question, why did that particular apple choose that unrepeatable instant to fall on that unique head, he might have written the history of an apple. Instead of which he asked himself why apples fell and produced the theory of gravitation. The decision was not the apple's but Newton's.

Davis was metaphorically struck by landscape and chose to write a history of it.

Fifthly, the open-system mentality directs the study of geomorphology to the whole landscape assemblage, rather than simply to the often minute elements of landscape having supposed evolutionary significance.

Sixthly, the open-system approach encourages rigorous geomorphic studies to be carried out in those regions—and perhaps these are in the majority—where the evidence for a previous protracted erosional history is blurred, or has been removed altogether.

Lastly, open-system thinking, when applied to geomorphology, has application within the general framework of geography; for geomorphology has always influenced geographical thinking to a great, and possibly excessive, degree (as, for example, that of Whittlesey, 1929; Darby, 1953; Beaver, 1961). Open-system thinking is characteristically less rigidly deterministic in a causative and time sense than the closed-system approach. The application of this closed-system approach to problems of human geography is extremely dangerous because, of its nature, it directs the emphasis toward a narrow determinism, and encourages a concentration upon closed boundary conditions, upon the tendency toward homogeneity and upon the leveling down of differences. Open-system thinking, however, directs attention to the heterogeneity of spatial organization, to the creation of segregation, and to the increasingly hierarchical differentiation which often takes place with time. These latter features are, after all, hallmarks of social, as well as biological, evolution.

ACKNOWLEDGMENTS

The author would like to thank Professor Ludwig von Bertalanffy of the University of Alberta and Dr. Luna B. Leopold of the United States Geological Survey for critically reading this manuscript and for making many valuable suggestions both regarding the general methodology and the application of general systems theory to geomorphology.

REFERENCES

Beaver, S. H., 1961, Technology and geography: The Advancement of Science, v. 18, p. 315–327.

Braun, E. L., 1950, Deciduous forests of eastern North America: Philadelphia, Pa. Blakiston Co., 596 p.

Bucher, W. H., 1941, The nature of geological inquiry and the training required for it: Am. Inst. Mining Metall. Engineers Tech. Pub. 1377, 6 p.

Burton, A. C., 1939, The properties of the steady state compared to those of equilibrium as shown in characteristic biological behavior: Jour. Cell. Comp. Physiol., v. 14, p. 327–349.

Chorley, R. J., 1957, Illustrating the laws of morphometry: Geol. Mag., v. 94, p. 140–149.

Clements, F. E., 1916, Plant succession: an analysis of the development of vegetation: Carnegie Inst. Washington, Pub. 242, 512 p.

Cole, M. M., 1960, Cerrado, Caatinga, and Pantanal: distribution and origin of the savanna vegetation of Brazil: Geog. Jour., v. 126, p. 168–179.

Culling, W. E. H., 1957, Multicyclic streams and the equilibrium theory of grade: Jour. Geology, v. 65, p. 259–274.

Darby, H. C., 1953, On the relations of geography and history: Inst. British Geog. Trans., no. 19, p. 1–11.

Denbigh, K. G., 1955, The principles of chemical equilibrium; with applications in chemistry and chemical engineering, Cambridge, England, Cambridge University Press, 491 p.

Denbigh, K. G., Hicks, M., and Page, F. M., 1948, The kinetics of open reaction systems: Faraday Soc. Trans., v. 44, p. 479–491.

Gilbert, G. K., 1877, Report on the geology of the Henry Mountains: 2d ed. 1880, Washington, D.C., Government Printing Office, 170 p.

——— 1886, The inculcation of the scientific method by example: Am. Jour. Sci., 3d ser., v. 31, p. 284–299.

——— 1914, The transportation of debris by running water: U.S. Geol. Survey Prof. Paper 86, 263 p.

Gleason, H. A., 1926–27, The individualistic concept of the plant association: Bull. Torrey Bot. Club, v. 53, p. 7–26.

——— 1927, Further views on the succession-concept: Ecology, v. 8, p. 299–326.

Glock, W. S., 1931, The development of drainage systems: Geog. Rev., v. 21, p. 475–482.

Hack, J. T., 1960, Interpretation of erosional topography in humid temperate regions: Am. Jour. Sci., v. 258–A, p. 80–97.

Hack, J. T., and Goodlett, J. C., 1960, Geomorphology and forest ecology of a mountain region in the central Appalachians: U.S. Geol. Survey Prof. Paper 347, 66 p.

Hall, A. D., and Fagen, R. E., 1956, Definition of system: General Systems Yearbook, v. 1, Ann Arbor, Mich., p. 18–28 (mimeographed).

Horton, R. E., 1945, Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology: Geol. Soc. America Bull., v. 56, p. 275–370.

Krumbein, W. C., 1959, The "sorting out" of geological variables, illustrated by regression analysis of factors controlling beach firmness: Jour. Sed. Petrology, v. 29, p. 575–587.

Leopold, L. B., and Maddock, T., Jr., 1953, The hydraulic geometry of stream channels and some physiographic implications: U.S. Geol. Survey Prof. Paper 252, 57 p.

Little, J. M., 1940, Erosional topography and erosion: San Francisco, Calif., A. Carlisle and Co., 104 p.

Mackin, J. H., 1948, Concept of the graded river: Geol. Soc. America Bull., v. 59, p. 463–512.

Melton, M.A., 1957, An analysis of the relation among elements of climate, surface properties, and geomorphology: Office of Naval Research Project NR 389–042, Tech. Rept. 11, Dept. Geol., Columbia Univ., 102 p.

Playfair, J., 1802, Illustrations of the Huttonian theory of the earth: Facsimile reprint, Champagne, Ill., Univ. Illinois Press, 1956, 528 p.

Postan, M., 1948, The revulsion from thought: The Cambridge Jour., v. 1, p. 395–408.

Prigogine, I., and Defay, R., 1954, Chemical thermodynamics: London, Longmans, Green and Co., 543 p.

Reiner, J. M., and Spiegelman, S., 1945, The energetics of transient and steady states, with special reference to biological systems: Phys. Chem. Jour., v. 49, p. 81–92.

Schumm, S. A., 1956, Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey: Geol. Soc. America Bull. v. 67, p. 597–646.

Strahler, A. N., 1950, Equilibrium theory of erosional slopes, approached by frequency distribution analysis: Am. Jour. Sci., v. 248, p. 673–696, 800–814.

——— 1952A, Dynamic basis of geomorphology: Geol. Soc. America Bull., v. 63, p. 923–938.

——— 1952B, Hypsometric (area-altitude) analysis of erosional topography: Geol. Soc. America Bull., v. 63, p. 1117–1142.

——— 1954, Statistical analysis in geomorphic research: Jour. Geology, v. 62, p. 1–25.

——— 1958, Dimensional analysis applied to fluvially dissected landforms: Geol. Soc. America Bull., v. 69, p. 279–300.

Thompson, D'Arcy W., 1942, On growth and form: Cambridge, England, 1116 p.

Von Bertalanffy, L., 1950, The theory of open systems in physics and biology: Science, v. 111, p. 23–29.

——— 1951, An outline of general system theory: Jour. British Phil. Sci., v. 1, p. 134–165.

——— 1952, Problems of life: Watts and Co., London, 216 p.

——— 1956, General system theory: General Systems Yearbook, v. 1, Ann Arbor, Mich., p. 1–10 (mimeographed).

——— 1960, Principles and theory of growth; Chapter 2 *in* Fundamental aspects of normal and malignant growth: Edited by W. W. Nowinski, Amsterdam, Elsevier Pub. Co., p. 143–156.

Whittaker, R. H., 1955, A consideration of the climax theory: the climax as a population and pattern: Ecol. Monographs, v. 23, p. 41–78.

Whittlesey, D., 1929, Sequent occupance: Assoc. American Geog. Ann. v. 19, p. 162–165.

Wolman, M. G., 1955, The natural channel of Brandywine Creek, Pennsylvania: U.S. Geol. Survey Prof. Paper 271, 56 p.

Wolman, M. G. and Miller, J. P., 1960, Magnitude and frequency of forces in geomorphic processes: Jour. Geology, v. 68, p. 54–74.

Wooldridge, S. W., and Goldring, F., 1953, The Weald: London, Collins, 276 p.

Wooldridge, S. W., and Linton, D. L., 1955, Structure, surface and drainage in south-east England: London, G. Philip and Son Ltd., 176 p.

U S. GOVERNMENT PRINTING OFFICE: 1962