EARTH SCIENCE JOURNAL Vol. 2, No. 2, 1968

DISTINGUISHING BETWEEN THE CONCEPTS OF STEADY STATE AND DYNAMIC EQUILIBRIUM IN GEOMORPHOLOGY

ATHOL D. ABRAHAMS

Department of Geography, University of Sydney

Abstract

The development of the concept of equilibrium in geomorphology over the past 15 years has been marked by linguistic difficulties due, in part, to the interchangeable use of the terms, dynamic equilibrium and steady state. It is here proposed that the range of steady state conditions constitute a sub-set of the range of conditions of dynamic equilibrium.

The application of General Systems Theory is responsible for the introduction to geomorphology of the term steady state which in the strictest sense refers to the tendency for constant forms to develop. Gilbert understood dynamic equilibrium to mean an adjustment between the processes of erosion and the resistance of the bedrock. More recently, Leopold and Langbein described dynamic or quasi-equilibrium as a state of energy distribution which does not necessarily involve any regularity of form. However, dynamic equilibrium finds expression over space and time, in the evolving regularity and mutual adjustment of form elements. The development of regular erosional landforms reflects the tendency of the energy conditions of a system to make the final adjustment to the most probable state. If the manner of landform evolution is the point in question, the concepts of dynamic equilibrium and steady state become clearly distinguishable and system boundaries must be precisely defined. In field studies the theoretical approach is often superseded by the pragmatic approach. However, unless the logical distinction between the two concepts is made in the first place confusion will continue to persist in geomorphic analysis.

The introduction of General Systems Theory into Geomorphology was characterised by the apparent interchangeability of the terms dynamic equilibrium and steady state. The equation of these concepts has since been described as the *dynamic* or *timeless* approach to the study of geomorphic phenomena. This approach is purposeful in the investigation of the rapport that exists between form and process when only empirical relations among variables independent of time are considered. However, in the study of form for its own sake and in studies involving the evolution of form properties, the historical parameter of time and the associated concept of adjustment become the chief considerations in geomorphic analysis.

The development of the concept of equilibrium in geomorphology over the past 15 years has been marked by linguistic difficulties which have been responsible for continual confusion in the literature. This confusion can be eliminated in part with the recognition of a meaningful distinction between the concept signifying adjustment (dynamic equilibrium, quasi-equilibrium or grade) and the concept signifying the tendency for constant forms to develop (steady state). In terms of elementary mathematical set theory, the range of steady state conditions constitutes a sub-set of the range of conditions of dynamic equilibrium (Figure 1).

Steady state conditions necessarily imply dynamic equilibrium (no matter what the time span being considered) but evidence for dynamic equilibrium does not always mean that form is remaining constant with the passage of time. This paper, it is hoped, will not only help to clarify the present concept of equilibrium but will also encourage a thoughtful use of the terms steady state and dynamic equilibrium.

The Steady State

The application of General Systems Theory is responsible for the introduction of the term steady state to geomorphology. Geomorphic systems, involving import and export of matter and energy across system boundaries, bear close resemblance

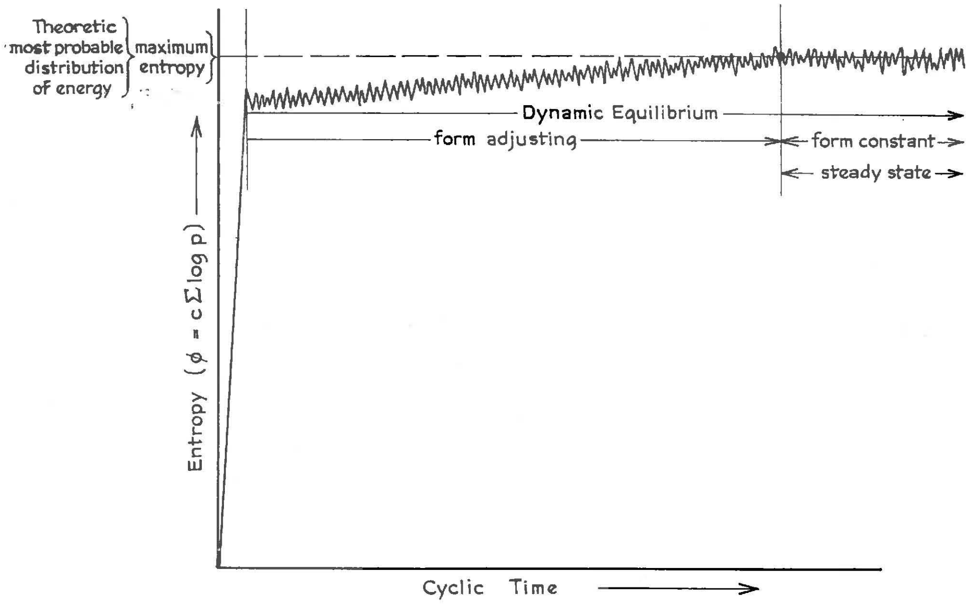

Figure 1. The concepts of dynamic equilibrium and steady state in geomorphology are expressed in terms of energy distribution. Average external energy conditions are assumed constant over the cyclic time span here considered. Entropy (ϕ) is defined statistically in terms of the probability (p) of a given physical state occurring as opposed to all other possible alternative states in the system (Leopold and Langbein, 1962). The diagram may be understood to represent a discrete element of a drainage basin, in which case, only temporary steady state conditions, associated with a constant level of entropy, may be achieved. With the passage of time the steady state may eventually be superseded as basin relief is lowered. Alternatively, if the system illustrated by the diagram is taken to represent a complete drainage basin, the steady state represents the static equilibrium of ultimate planation.

to classical open systems which were first proposed in thermodynamics (Defay, 1929) and biology (Bertalanffy, 1932). The chief advantage of the open system approach to geomorphic investigation lies in its emphasis on the interaction of process and form, and in the ability of the open system to attain a steady state, wherein the import and export of material and energy are equated by means of an adjustment of the form of the system itself.

> "The system remains *constant*[1] as a whole and in its phases; though there is a continuous flow of the component materials"
>
> (Bertalanffy, 1950, p. 23)

The steady state of an open system, according to Prigogine (1955, p. 82) is characterised by a constant level of entropy (which need not be the maximum possible in the system) at which the rate of increase in entropy is an absolute minimum (i.e., zero). With this premise the continuity equation of Denbigh (1951, p. 40) takes the form that the rate of outflow of energy equals the rate of internal generation of entropy — that is, the rate at which mechanical (potential or free) energy is dissipated into heat in passing through the system is equal to the inflow of free energy (i.e., negative entropy). The "organised" state (for example, drainage density) of the system thus achieves, and is maintained at, a constant value in balance with the through-flow of material and energy. The steady state however depends on conditions imposed on the boundaries of the system, and is maintained only so long as external conditions remain unchanged.

[1] The italics are those of the author A.D.A.

Although virtually all geomorphic systems are open, in that they exchange both mass and energy with their surroundings, Prigogine's Theorem is generally irreconcileable with the sequential loss of a component of potential energy on account of the progressive reduction of relief. For in systems of progressively increasing entropy, the steady state can only be achieved in a static condition of maximum entropy. This characteristic is reminiscent of closed systems and of the historical approach to landform analysis. With the recognition of an element of continuing degradation within a drainage basin, the concept of steady state must imply the static equilibrium of ultimate planation.

Although open geomorphic systems undergoing conditions of increasing entropy (e.g., drainage basins controlled by a constant base level) cannot be thought of as exemplifying steady state conditions, the evidence of a host of workers (many of whom are reported in Leopold, Wolman and Miller, 1964) does indicate that certain *elements* of the drainage basin (i.e., hillslope segments) are adjusted to the present environment in such a way that form changes occurring over time are not purely functions of the length of time elapsed. These adjusted form elements, which are constant, may usefully be considered as manifesting steady states in open systems.

Gilbert's Concept of Dynamic Equilibrium

The idea of dynamic equilibrium as a state of balance or adjustment between the processes of erosion and the resistance of the rocks originated with Gilbert (1876, 1877, 1880). Gilbert conceived of the idea of dynamic equilibrium within the context of his graded stream and later extended the concept to incorporate the whole drainage system including all transportational slopes (Chorley and others, 1964, pp. 550-62). In 1876 Gilbert wrote:

> "In general we may say that a stream tends to equalise its work in all parts of its course . . . . When its work is to corrode and the resistance is unequal, it concentrates its energy where the resistance is great by crowding many feet of descent into a small space . . . When its work is to transport the resistance is constant and the fall is evenly distributed by a uniform grade" (p. 100).

The balance Gilbert conceives of is an adjustment between erosive forces on the one hand and resistance of the bedrock on the other. His analysis in terms of equilibrium is independent of time, for while Gilbert recognised evolutionary change, time or stage for him had nothing to do with a stream's ability to transport the eroded materials, or with the amount of relief or ruggedness of the terrain.

> "Gilbert was primarily concerned with the manner in which equilibrium landforms become adjusted to geomorphic processes, and an interest in the progress towards such adjustment and the changes to which such adjustment is susceptible through time replaced for him a simple cyclical basis such as that which preoccupied Davis" (Chorley, 1965, p. 150).

For Gilbert, equilibrium over a whole drainage system was achieved between the Law of Structure and the Law of Uniform Slopes, when . . .

> " . . . the ratio of erosive action, as dependent on declivities, became equal to the ratio of the resistances as dependent upon rock character" (1877, p. 116).

This concept of adjustment Gilbert termed *equality of action* or *dynamic equilibrium.*

Crucial also to Gilbert's scheme was the recognition of the interdependence of the various elements of any one drainage system. As form is adjusted to process, variations in the rate of erosion in any part of the drainage basin will be translated with varying effects throughout all parts of the system. This interdependence is reflected in the development of the whole drainage system in a state of dynamic equilibrium.

The Concepts of Steady State and Dynamic Equilibrium in Contemporary Geomorphic Studies

It was not until after a lapse of 70 years that the principles advocated by Gilbert were incorporated in geomorphic thinking within the more sophisticated framework of General Systems Theory (Strahler, 1950, 1952a, 1952b; Hack, 1960, 1965, 1966; Hack and Goodlett, 1960; Chorley, 1956, 1962, 1966; Schumm, 1956; Schumm and Lichty, 1965; Holmes, 1964; Howard, 1965).

Leopold and Langbein (1962, 1964), in their consideration of the concept of dynamic or quasi-equilibrium, go beyond the findings of previous workers. They examine landscape form in terms of concepts borrowed from the probabilistic interpretation of entropy. These concepts include the tendency towards a condition of least work and that towards the equal distribution of energy. When these tendencies operate, each opposes the other: the dynamic or quasi-equilibrium position is intermediate between the limits towards which they respectively lead. When two such opposing tendencies can be described mathematically, the most probable condition between them can also be expressed (Leopold and Langbein, 1964).

Hack (1960) and Leopold and Langbein (1962) argue, although from different theoretical precepts, that the most probable (energy) state is not a sensitive one. That is, a state approaching the most probable can be arrived at very quickly . . .

> " . . . although the rate of adjustment to the theoretic most probable state there after may be quite slow if ever achieved" (Leopold and Langbein, 1962, p. A4) (Figure 1).

Whether a system can attain this most probable state, in the final phase of adjustment, depends on the constraints that lithology, structure and history place on the distribution of energy. It is the adjustment to these constraints, involving an evolution in form, that has been termed dynamic or quasi-equilibrium. This mutual adjustment among the various parameters of a drainage basin is manifested in the Laws of Morphometry and in the regular downstream variation of the hydraulic geometry in open channels. Leopold and Langbein (1962, p. A19) conclude:

> "Landscape evolution may be viewed as an evolution in the nature of constraints in time, maintaining through time essentially a dynamic or quasi-equilibrium."

Dynamic equilibrium may therefore be considered as a *state of energy distribution* which is always arrived at quickly in response to a changing energy balance. When initially achieved, *this state may involve no great regularity of form* (Holmes, 1964). However, dynamic equilibrium finds expression, over time and space, in the evolving regularity and mutual adjustment of form elements. The development of regular erosional landforms reflects the tendency of the energy conditions of a system to make the final adjustment to the most probable state.

The trend of recent literature (Dury, 1967; Chorley, 1962, 1966; Hack, 1965) is to recognise that the environment, particularly climate, is in practice never stable long enough to allow all the elements of the landscape to make the final adjustment to the most probable (steady) state. Always there exists in form some degree of time-lag. Most existing features are thought to be a product both of former and of very late to present energy-conditions. For Chorley (1962), the degree to which later conditions have gained ascendency over the former is a function of the ratio between the amount of present energy-application and the strength of the landscape materials (also see Holmes, 1964).

Some parameters, such as those of the hydraulic geometry of a stream which flows through unconsolidated material undergo very rapid form adjustment, in response to a changing fieldforce. However, as Leopold and Maddock point out, the slope of the channel . . .

> " . . . is one hydraulic factor which can be adjusted over a period of time by processes within the stream and may be considered the factor which makes the final adjustment, as may be required for quasi-equilibrium" (1953, p. 52).

At the other end of the scale the form aspect of relief evolves very slowly in response to the changing energy balance: thus, channel slope adjusts very slowly. Relief will, for long periods, reflect past adjustments of form to differing force to strength ratios (Chorley, 1966). Although the state of dynamic equilibrium may be arrived at quickly, the form elements related to relief may never have long enough to achieve the steady state, particularly as relief itself declines "owing to" the passage of time.

While it is true that "the progressive loss of a component of potential energy due to relief reduction" (Chorley, 1962, p. B3) precludes a drainage basin from attaining a steady state, it is wrong to assume that all the properties of the drainage system are necessarily involved in a progressive sequential change. There seems no reason that drainage density (Schumm, 1956; Chorley, 1965), maximum valley-side slope (Strahler, 1950) or basin area and configuration (Gilbert, 1880; Bertalanffy, 1956; Schumm, 1956; Chorley, 1962) should change continuously in association with reduction of relief.

Whether landforms remain constant or are degraded as a function of time becomes a matter for empirical investigation. However, so long as the various forms may be shown as adjusting to the present erosional environment, the term dynamic equilibrium is applicable. Gilbert's conception of dynamic equilibrium involved the whole drainage system and was in no way delimited in time or over space. It is here maintained, in view of the support and more precise meaning that the findings of Leopold and Langbein (1962, 1964) have lent to Gilbert's concept, that it is imperative that the notion of dynamic equilibrium be freed from that of steady state. The idea of dynamic equilibrium is applicable to every open geomorphic system and may be understood as a state of energy distribution which finds expression in the " . . . adjustment [and interadjustment] of the internal [form] variables to external [energy] conditions" (Howard, 1965, p. 305). Thus defined, the concept of dynamic equilibrium need neither be delimited over time and space, nor need the term dynamic equilibrium necessarily imply a steady state.

Schumm and Lichty (1965) have attempted to resolve the confusion that has arisen from the equation of the notions of dynamic equilibrium and steady state in some geomorphic literature. They suggest that the *dynamic* approach developed by Strahler (1950, 1952b) and Hack (1960) and encouraged by Chorley (1962) . . .

> " . . . need not be a break with tradition but is simply a method of considering the landscape within narrow temporal limits" (1965, p. 111)

— that is, in landform studies, the criteria whereby a system in adjustment (dynamic equilibrium) may be considered as manifesting a steady state depend primarily upon the aim of the investigation.

If the study is directed purely at the manner and operation of erosional processes and their effects on landforms the investigator is unconcerned with time and the study is *dynamic* or non-cyclic in character. The progressive loss of relief is, both in theoretical terms and in practical measurement, meaningless and irrelevant in the analysis of the landform system. The concept of equilibrium in non-cyclic studies may be truly considered analogous to that of classical open systems in thermodynamics. Only in such studies, which are *divorced from time*, can (as a working assumption) the terms dynamic equilibrium and steady state be treated as interchangeable.

Alternatively, if the manner of landform evolution is the point in question, then the concepts of dynamic equilibrium and steady state become clearly distinguishable. Unless one has in mind a static state of ultimate planation over a whole landscape, then only discrete elements of a drainage basin may be regarded as manifesting a (most probable) steady state when form is maintained as denudation continues (for example, the parallel retreat of a hillslope segment). The idea of a steady state is inapplicable to an entire drainage system (except ultimate planation be envisaged) over even the shortest time span, for sediment is always being transported out of the system. Schumm and Lichty (1965) emphasise that employment of the concept of steady state in geomorphology should be confined to systems of which the boundaries have been defined precisely both in terms of time and of spatial relations.

The steady state in timebound studies of the evolution of geomorphic systems both implies and is always preceded by an energy state of dynamic equilibrium (Figure 1). The idea of dynamic equilibrium (quasi-equilibrium or grade) as essentially an expression of energy distribution, arrived at almost immediately and possessing no "converse idea of an ungraded state" (Dury, 1966), detracts from the meaning of the concept in the consideration of form. However, in so far as the energy concept of dynamic equilibrium may be manifested in, and is essential to our understanding of, the adjustment and interadjustment of form variables (illustrated in the Laws of Morphometry), the concept is not entirely unserviceable to geomorphology (*cf.* Dury, 1966). Although dynamic equilibrium is recognisable as an energy concept, the inability to define dynamic equilibrium precisely in terms of form has been responsible for many of the difficulties encountered in early discussions on the concept of grade, and has prompted more recent quantitative workers to employ terms such as "approximate" or "quasi-" equilibrium.

The concept of steady state, however, does have a precise meaning in terms of form and although difficulties may arise in the consideration of varying time and spatial relations, the concept is both meaningful and purposeful in field studies and in the theoretical analysis of landforms generally.

The steady state, however, is rarely one of precise poise, and continual fluctuations about the most probable condition can be expected in accordance with the magnitude and frequency of the fieldforce and overshooting of feedback mechanisms (Figure 1). Although an important logical distinction can be drawn between the concept of adjustment (dynamic equilibrium) and the notion of steady state, a pragmatic approach is bound to supersede one based on purely logical considerations for those parameters highly sensitive to a changing fieldforce. When the orderly changes towards maximum entropy associated with declining drainage relief are infinitesimal compared to other non-timebound changes in the system, it becomes in actuality very difficult to distinguish between the concepts of adjustment and steady state. Perhaps it is for this reason that much confusion continues to cloud the problem of equilibrium in geomorphology. Unless the logical distinction between the two concepts is made in the first place, this confusion is likely to continue.

ACKNOWLEDGEMENTS

I wish to thank Mr Ken Page for his stimulating comments and his thoughtful assistance in preparing this manuscript. I am also indebted to Professors G. H. Dury and T. Langford-Smith, of Sydney University, for critically reading this text and making many helpful suggestions.

REFERENCES

Bertalanffy, L., 1932: *Theoretische Biologie.* Erster Band. Berlin.

——————, 1950: The theory of open systems in physics and biology. *Science.* 3: pp. 23-29.

——————, 1956: General systems theory. *Gen. Syst.* 1: pp. 1-10.

Chorley, R. J., 1956: Some neglected source material in quantitative geomorphology. *Jnl. Geol.* 64: pp. 422-423.

——————, 1962: Geomorphology and general systems theory. *U.S. Geol. Surv. Prof. Pap.* 500-B: 10 pp.

——————, 1965: A re-evaluation of the geomorphic system of W. M. Davis. In R. J. Chorley and P. Haggett: *Frontiers in Geographical Teaching.* London: pp. 21-38

——————, 1966: The application of statistical methods to geomorphology. In G. H. Dury: *Essays in Geomorphology.* London: pp. 275-387.

Chorley, R. J., Dunn, A. J., and Beckinsale, R. P., 1964: *The History of the Study of Landforms.* Vol. 1. London: 678 pp.

Defay, R., 1929: Introduction à la thermodynamique des systems ouverts. *Acad. Roy. de Belgique. Bull. Classe des Sciences.* 53 Serie 15: pp. 678.

Denbigh, K. G., 1951: *The Thermodynamics of the Steady State.* London: 103 pp.

Dury, G. H., 1966: The Concept of Grade. In G. H. Dury: *Essays in Geomorphology.* London: pp. 211-234.

——————, 1967: Climatic change as a geographical backdrop. *Aust. Geogr.* 10: pp. 231-242.

Gilbert, G. K., 1876: The Colorado Plateau Province as a field for geological study. *Amer. Jnl. Sci.* 12: pp. 16-24, 85-103.

——————, 1877: Report on the geology of the Henry Mountains. *U.S. Geog. and Geol. Surv. Rocky Mtns Regions* 160 pp.

——————, 1880: Contributions to the history of Lake Bonneville. *U.S. Geol. Surv., 2nd Ann. Rept.*: pp. 167-200.

Hack, J. T., 1960: Interpretation of erosional topography in humid temperate regions. *Amer. Jnl. Sci.* 558-A (Bradley Volume) : pp. 80-97.

——————, 1965: Geomorphology of the Shenandoah Valley, Virginia and West Virginia and origin of the residual ore deposits. *U.S. Geol. Surv. Prof. Pap.* 484: 84 pp.

Hack, J. T. and Goodlett, J. C., 1960: Geomorphology and forest ecology of a mountain region in the Central Appalachians. *U.S. Geol. Surv. Prof. Pap.* 347: 66 pp.

Holmes, C. D., 1964: Equilibrium in humid-climate physiographic processes. *Amer. Jnl Sci.* 262: pp. 436-445.

Howard, A. D., 1965: Geomorphological systems — equilibrium and dynamics. *Amer. Jnl Sci.* 263: pp. 302-312.

Langbein, W. D., and Leopold, L. B., 1964: Quasi-equilibrium states in channel morphology. *Amer. Jnl. Sci.* 262: pp. 782-794.

Leopold, L. B., and Maddock, T., 1953: The hydraulic geometry of stream channels and some physiographic implications. *U.S. Geol. Surv. Prof. Pap.* 252: 57 pp.

Leopold, L. B., and Langbein, W. B., 1962: The concept of entropy in landscape evolution. *U.S. Geol. Surv. Prof. Pap.* 500-A: 20 pp.

Leopold, L. B., Wolman, M. G., and Miller, J. P., 1964: *Fluvial Processes in Geomorphology.* San Francisco: 522 pp.

Prigogine, I., 1955: *Introduction to Thermodynamics of Irreversible Processes.* Springfield, Ill.: 115 pp.

Schumm, S. A., 1956: Evolution of drainage system and slopes in badlands at Perth Amboy, New Jersey. *Geol. Soc. Amer. Bull.* 67: pp. 597-646.

Schumm, S. A., and Lichty, R. W., 1965: Time, space and causality in geomorphology. *Amer. Jnl. Sci.* 263: pp. 110-119.

Strahler, A. N., 1950: Equilibrium theory of erosional slopes approached by frequency distributional analysis. *Amer. Jnl. Sci.* 248: pp. 673-696, 800-814.

——————, 1952a: Dynamic basis of geomorphology. *Geol. Soc. Amer. Bull.* 63: pp. 923-938.

——————, 1952b: Hypsometric (area-altitude) analysis of erosional topography. *Geol. Soc. Amer. Bull.* 63: pp. 1117-1142.