MODELS OF LANDSCAPE EVOLUTION

Intellectual structures are critical in geomorphology because:

1. **Landforms develop over longer timespans (usually much longer) than human lifespans**
   - therefore, we resort to analogues either in the present or historical records to explain the evolution of landscapes
   - the extrapolation of short records over long timespans requires a theoretical basis

2. **There are different methodologies and objectives depending on the relevant theory**
   - this is most apparent in the contrast between research which links characteristic form to present day processes (and thus limits retrodiction and prediction) versus research that focuses on relaxation forms but does not address relationships between contemporary forms and processes
   - appreciation of theory leads to recognition that there is an artificial entry point to this circular argument and that the starting point will often depend on the nature of a landscape and objectives of the study

3. **By its unique nature, erosion eliminates evidence of landscape evolution**
   - thus, we depend very much on depositional records (stratigraphy)
   - however rarely are depositional records continuous and gaps present significant challenges and opportunities for interpretation
   - just as we need a strong theoretical basis for extrapolating from short process records, the same applies to the use of fragmented depositional records

4. **The most profitable approach to landform studies is to derive hypotheses from process research and corroborate or falsify them with morphometric research**
   - however, for logistical and methodological reasons, process studies are local
   - once again, a conceptual framework is required to link scales and permit the testing of hypotheses about landscapes

Thus far we have considered a number of specific concepts within the context of time and space in geomorphology. Now we visit concepts in the context of models of landscape evolution. Thorn (1988: 121) uses the analogy of fabric; the concepts are individual threads in the fabric of geomorphology. When the concepts are woven together, a pattern merges, but they can be woven in a variety of designs at the weaver's (modellers) discretion. Thus, models are like fabric created by weaving together concepts in a pattern that embraces the various temporal and spatial scales of landform development.

W.M. Davis: The geographical cycle

- the first model of landscape evolution to gain widespread acceptance within the discipline
- was remarkably influential and persistent but no longer dominates research thinking like it did, but still used as a teaching tool and residual influence reflected in the way geomorphologists cling to cyclical models

W.M. Davis was geography professor at Harvard University. He wrote about his model from 1880-1938, travelled and spoke widely. Like his contemporaries in natural science, he was strongly influenced by Charles Darwin (On the Origin of the Species) and Charles Lyell (Principles of Geology), although used evolution as a notion of history (inevitable progress or change over time) rather than a process and took a deterministic rather than probabilistic view of evolution like Darwin.

Thus, Davis aspired to a deductive, theoretical, genetic model of landscape evolution. The concepts of structure, process and time were his theoretical framework:

- structure was regional and considered as an initial condition (beyond the scope of his model)
- process was the sum of weathering and transport rather than specific processes or mechanisms, although since his cycle was based on the assumption of a normal climate, *i.e.,* humid temperate, fluvial processes predominate
- time was the central theme, but time in the sense of landscape development relative to the completion of the entire geographical cycle, *i.e.*, extent of landscape development or stage

Walter Penck: relating landforms to crustal movements

- similar to Davis in terms of morphological and deductive but failure to relate hypothesized forms and field observations

- but whereas Davis related form to stage, Penck related it to rate of uplift and he rejected Davis' assumption that uplift is followed by erosion of a stable crust
- he didn't see a sequence of landform development but rather various possible sequences according to differing rates of uplift and erosion
- he was careful to define the domain of his model as sub-aerial, but excluding aeolian and glacial processes and climatic variability

The best-known manifestation of Penck's model is the retreating slope profile, where evolution of the profile is controlled by rate of output (river erosion) at the base and rate of uplift of the land. He was able to deduce various slope profiles for different combinations of river erosion, uplift and rock resistance, by assuming that stronger rock requires steeper slopes for the same rate of denudation. He also modelled stream longitudinal profile as controlled by uplift, rock type and stream discharge.

Another expression of his model was three categories of landform assemblage according to tectonic history (versus normal climate):

- great folding from lateral forces (orogenic)
- dome formation without folding (epeirogenic)
- stable regions

Penck also envisaged three landscapes resulting from slow, intermediate and rapid rates of uplift. Morphologically, they were similar to Davis' old, mature and young stages, but whereas Davis ascribed morphology to age (time-dependent), Penck's model was largely time-independent based on tectonic history.

Evaluation of Penck's model is hindered by its hurried writing, posthumous publication and confused representation in English, including misrepresentation by Davis who was defending his own ideas. Although there were important flaws and contradictions in Penck's work, and it was poorly translated or misrepresented especially by adherents to the Davisian school, it was the one comprehensive alternative to the cycle of erosion and thus was a focus for contrary ideas, such as emphasis on process rate (both endogenic and exogenic) and greater attention to slope retreat.

Lester King: global geomorphology during the era of process studies

- King was trained in the Davisian school but eventually rejected many of Davis' notion as he attempted to apply the cycle of erosion to an interpretation of the landscape of South Africa

- his model is based on the notion of parallel retreat of scarps and the resulting constraint on the down wearing of the surface of the scarp

King's model was based on a slope profile consisting of four segments, any one of which may be entirely absent:

1. waxing slope: convex segment at the crest, dominated by soil creep of a weathered mantle; increasing slope angle is required to transport the greater quantity of slope debris with distance downslope
2. free face: bedrock outcrop; retreats parallel with weathering and uniform removal; may be absent in areas of low relief
3. debris slope: debris from the free face resting at the angle of repose; does not bury the free face but retreats with it
4. waning: gentle concave profile controlled by sheetwash and transport of sediment over an eroded bedrock surface (pediment)

- the corresponding sequence of landscape evolution would be expansion and coalescence of pediments (pediplanation to form pediplains) as the free face retreats eliminating the higher surfaces (older pediments) and creating isolated erosional remnants
- King suggested that this evolution of landscapes would occur everywhere, but regarded the arid cycle as dominant given its extent geographically and over geological time
- his model implies that slopes lacking the free face (*i.e.*, having the classic sigmoidal slope) are inactive and a degenerative from of his classic profile

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Systems modelling

Systems modelling swept through geomorphology in the 1960's with the shift to process and quantitative geomorphology. Although not directly related to process geomorphology, the two methodologies are so compatible that they are closely associated in the same manner as Davis" cycle of erosion and denudation chronology.

The formal structure of systems modelling (inputs, outputs, throughputs), and its application either conceptually or quantitatively make it a popular framework for research and teaching (hydrological cycle, continuity equations).

System
: a set of objects together with relationships between the objects and their attributes, or a set of objects and the common processes by which they interact

In geomorphology, objects are usually landscape elements at a particular scale, relationships are geomorphic processes and attributes are physical properties like slope gradient, soil texture or drainage density (also depending on scale).

The components of the system will depend on the relationships that the researcher or teacher considers important or relevant. A model is a simplification of a system that is assumed to exist in the real world. Since it will be based on selected parts of a system, the model will always be incorrect to some degree.

Scientists can agree on the definition of a particular system, but it can never be fully known. Conversely, a model can be simple and completely known, but always will be incomplete and useful only for specific purposes.

<u>Types of systems:</u>

1. isolated: assumed to have boundaries that prevent the import or export of energy and mass; besides the universe, the only isolated systems are in labs or assumed for convenience
2. closed: import or export of energy but not mass; the earth is closed to closed and some geomorphic systems can be modelled as if they are (*e.g.* an internal drainage basin)
3. open: both energy and mass move freely across system boundaries, includes most of the natural world

The isolated system is the basis for the concept of maximum entropy where free energy decreases, as it becomes more evenly distributed and moves along increasing lower gradients. However, in open systems, energy is input and output. Therefore, natural systems tend to adjust by self-regulation thereby approaching or remaining near an equilibrium (*e.g.*, circulation of the oceans and atmosphere in response to the global solar energy balance).

Types of system models according to complexity:

1. qualitative data, verbal description, graphs to describe a system; does not permit true modelling but is a first stage
2. identification and analysis of morphological variables (*e.g.* free face and talus); simplest model, only functional information is relative position of the components, but no inference or understanding of mass or energy exchange is possible
3. identification and analysis of energy and mass transfer; cascading system (direction specified; energy and mass move from the free face to the talus and not vice versa)
4. integration of form and process; unlike 3 these involve feedback, output from one part is input to another, opposing or slowing the general trend of the system (negative feedback) or magnifying the main trend (positive feedback); natural systems (except glacial systems) are characterized by negative feedback so that changes are resisted and tendency towards an equilibrium is maintained; thus change in relationships over time can be modelled, for example, the talus grows to bury the free face resulting in negative feedback and decreasing rates of mass wasting and talus slope growth over time
5. control systems: conscious or deliberate human intervention in the system; useful for addressing engineering or planning issues (impact assessment)

Types of system models according to degree of understanding of the system:

1. black box: nothing known except the relationship between input and output
2. grey box: structure is known (subsystems considered), but no detailed knowledge or investigation

3. white box: subsystems, storages and flows known and investigated in detail

Construction of a system model

- requires identification of the important morphological variables, and linkages among these in terms of direction and strength
- one of the simplest and most common quantitative techniques is correlation: that is establishing the covariation among pairs of variables using either nominal/ordinal data (non-parametric) or interval/ratio data (parametric)
- correlation does not distinguish between dependent and independent variables because variance in both variables is examined; therefore, cause and effect can only be determined by interpreting other evidence; linkages established in this manner represent only statistical relationships and no the flow of energy or matter
- the principal objective of science is to predict the behaviour of systems by determining the behaviour of individual components with absolute certainty using deterministic mathematics; this usually is not possible, so the behaviour of groups of objects is predicted with some known margin of error using the statistical methods of stochastic mathematics
- a fundamental between rational and empirical equations is that the former balance dimensionally, that is, when dimensions of mass, length, time and temperature are summed the units are either the same on both sides of an equation or result in dimensionless quantities, including angles; the advantage of deterministic modelling is prediction with certainty and dimensionless numbers apply to a range of scales, however energy and mass transfer models cannot be mathematically integrated given the dimensional incompatibility
- besides equations, relationships within and among subsystems are depicted with canonical structures usually as a schematic diagram as a geomorphic interpretation of a system model; these diagrams are able to show the nature (direct or inverse), direction (dependent/independent), and strength of linkages within and among subsets of variables; by following pathways it is possible to identify feedback
- the special significance of certain variables can be shown symbolically, in particular, regulators are variables that tend to stabilize the system internally (*e.g.* thresholds variables - slope angle, infiltration capacity; those that influence energy or mass transfer - vegetation; those that are important in terms of presence/absence - basal erosion), while stores are components that retain and then release energy, mass or information (*e.g.* vegetation, soil water, sediment sinks, energy sinks)

Evaluation of systems modelling

- the greatest strength is the consistent structure across a range of application, complexity and techniques

- the use of symbols is powerful means of simplification and abstraction and thereby enables the use of mathematical symbols
- greatest weakness if the choice was system components which is arbitrary and unscientific (there is no standard approach) and influences are further analysis and interpretation
- similar to the problem of distinguishing between core and peripheral variables is identifying the limits of the system, that is, defining boundaries
- systems models often are used just to present what is already known, that is, to summarize relationships by presenting them diagrammatically; this is problem of application and not the methodology; systems models should be related to theory by displaying new relationships and serving to generate hypotheses
- system models are abstractions not reality, they must be tied to theory and treated as simplifications with limitations

John T. Hack: A time-independent model

The interactions of time and space add much complexity to modelling. Thus, usually one theme is dominant and the other produces variability or noise. Traditionally time-dependent models were more readily accepted because they were compatible with the popular notion of evolution and slow change over time and qualitative descriptive investigation, and because the approach was advocated by W.M. Davis, the pre-eminent American geomorphologist. Davis, King and Penck (in that order) placed most, less and lesser emphasis on time, respectively. King also focused on process while Penck emphasized structure and process. These themes have a spatial component, although King and to a lesser extent Penck related landscapes to initiating (past) events (*e.g.* tectonic history). Davis' contemporary G.K. Gilbert had a methodology that was founded on principles of physics and engineering and was more suited to a time-independent approach. However Gilbert made no attempt to develop or champion a comprehensive model. With the quantitative revolution and shift to process geomorphology, there was renewed interest in Gilbert and attention to a time-independent perspective.

John T. Hack is the champion of a time-independent model where landscape variability due to age is not modelled, but rather considered a source of variability in landscape from related to contemporary process. This approach assumes a dynamic equilibrium between contemporary surficial processes and the surface upon which they are acting. Hack chose dynamic equilibrium as his conceptual and methodological framework. He derived this perspective directly from G.K. Gilbert who worked in the western US, where the dramatic semiarid landscape seems youthful and dynamic. Hack applied dynamic equilibrium to reinterpretation of the Appalachian Mountains, the landscape that led Davis to think in terms of change over time.

The time-independent perspective of Gilbert is reflected in his "laws" of

- uniform slope: non-linear increase in rate of erosion with slope angle
- structure: differential erosion on resistant and non-resistant substrata
- divides of increasing acclivity: stream and slope gradients increase towards divides

- tendency of equality of action: same rates of erosion on hard and soft rocks through adjustment of slope angles; steep and high relief in strong rocks, low gradient and relief in weak rocks

These laws all reflect a perspective of spatial variation and dynamic equilibrium between forces and resistance.

The basic features of dynamic equilibrium as applied to spatial relations within a drainage basin by Hack:

- all elements of the topography are mutually adjusted so that they are downwasting at the same rate
- forms and processes are in a steady state of balance
- differences and characteristics of form are explainable in terms of spatial relations in which geologic patterns are the primary consideration rather than a theoretical evolutionary development
- opposing forces (inputs and outputs) are in a state of balance where their effects cancel out to produce a steady state

Theory of J.T. Hack:

American geomorphologist J.T. Hack made a serious attempt to fill the conceptual vacuum created by the criticism and rejection of Davisian evolutionary model of geographical cycle and Penck's morphological system. Hack pointed out that multi-level landscape (polycyclic relief) cannot be explained in terms of multiple erosion cycle (Davisian notion), rather these landscapes can be explained in terms of dynamic equilibrium theory.

According to Hack, geomorphic system is an open system and so long as energy remains constant in the geomorphic system, landscape remains in the steady state condition despite the lowering in the landscape by denudational processes. Hack's model envisages time-independent development of landscape. In other words, "the shape of the landforms reflects the balance between the resistance of the underlying materials to erosion and the erosive energy of the active processes".

The main assumptions of the Hackian model of landscape development are:

(a) There is balance between denudational processes and rock resistance.

(b) There is uniform rate of downwasting in all components of landscapes.

(c) Differences and characteristics of form are explicable in terms of spatial relations in which geologic patterns are primary consideration.

(d) The denudational processes which operate at present have been carved out of the earth's surface landscapes.

(e) There is lithologic adjustment to landforms.

Hack also maintained that his model is not comprehensive, that time can also be invoked to explain landscape features, but it does apply to the entire range of spatial scales of interest to geomorphologists. Under dynamic equilibrium, landscapes evolve without obvious change, unless there is a change in energy inputs (climatic change, tectonism) or surface resistance. Examples of the latter include the denudation of surface materials to expose harder or softer materials, or the accumulation of coarse materials in valley bottoms. The consequent adjustment to these changes represents a disequilibrium but does not conflict with the time-independent perspective. Hack argued like Penck that rates of uplift and erosion are linked, although he related erosion plus relief to uplift and rock resistance and had a thin database to support this relationship.

Evaluation of dynamic equilibrium:

1. the past usually is poorly or only partly known, thus a model based on current conditions has a definite advantage
2. mutual relationship with process geomorphology
3. time-independent is an end-member of the distribution of systems and system models; these are fairly easily identified (*e.g.* and underfit stream is time-dependent relative to valley form but time-independent with respect to channel form)
4. however, it is not usually this easy to resolve the complex forms that represent both time-independent and time-dependent behaviour; attention to spatial and temporal scale help, for example time-independent behaviour is more likely at more local scales, and the influence of past processes is proportional to their intensity and inversely proportional to time elapsed since the event
5. dynamic equilibrium implies characteristic forms as opposed to relaxation forms
6. situations where form is not maintained include uplift exceeding rates of erosion or increasing relief controlled by difference in rock resistance (*e.g.*, inversion of topography)
7. When small segments of landscape evolution are sampled, it becomes difficult or impossible to distinguish between dynamic equilibrium (trending mean), steady state (constant mean) and dynamic metastable equilibrium (two scales of oscillations). Hack referred to both steady state and dynamic equilibrium, however a trending mean is much more likely in geomorphic systems.
8. Dynamic equilibrium is more of a conceptual framework than a fully tested corroborated model, which will require much more extensive data bases. However, it is a very useful framework in that the reduced role of time is replaced with an expansion of spatial variability and the integration of parts of landscapes. In this respect it is tied to a systems approach and the notion that systems move toward equilibrium at a rate proportional to their distance from it. Thus those far from equilibrium change quickly (time-independent) and thus near equilibrium change slowly (time-dependent). This systems perspective unites both the time-dependent and time-independent viewpoints.