9

FORCE-RESISTANCE

Energy, both kinetic and potential, is derived from solar radiation, gravity, and the Earth's geothermal energy, and is recycled partly through physical and biochemical processes and by human impact. This produces forces that determine the character of major categories of Earth surface processes. Statistical mechanics and gravity-driven fluid forces provide the basis for the analysis of many surface processes, with theoretical understanding assisted by the development of models and the availability of quantitative methods. Ideally mathematical statements would describe a model based on physical principles applicable to all surface processes. Hitherto a hierarchy of models has been employed, many involving force, resistance, stress and strain, progressing to the production of geomorphic transport laws, with models including hybrid indices such as factor of safety.

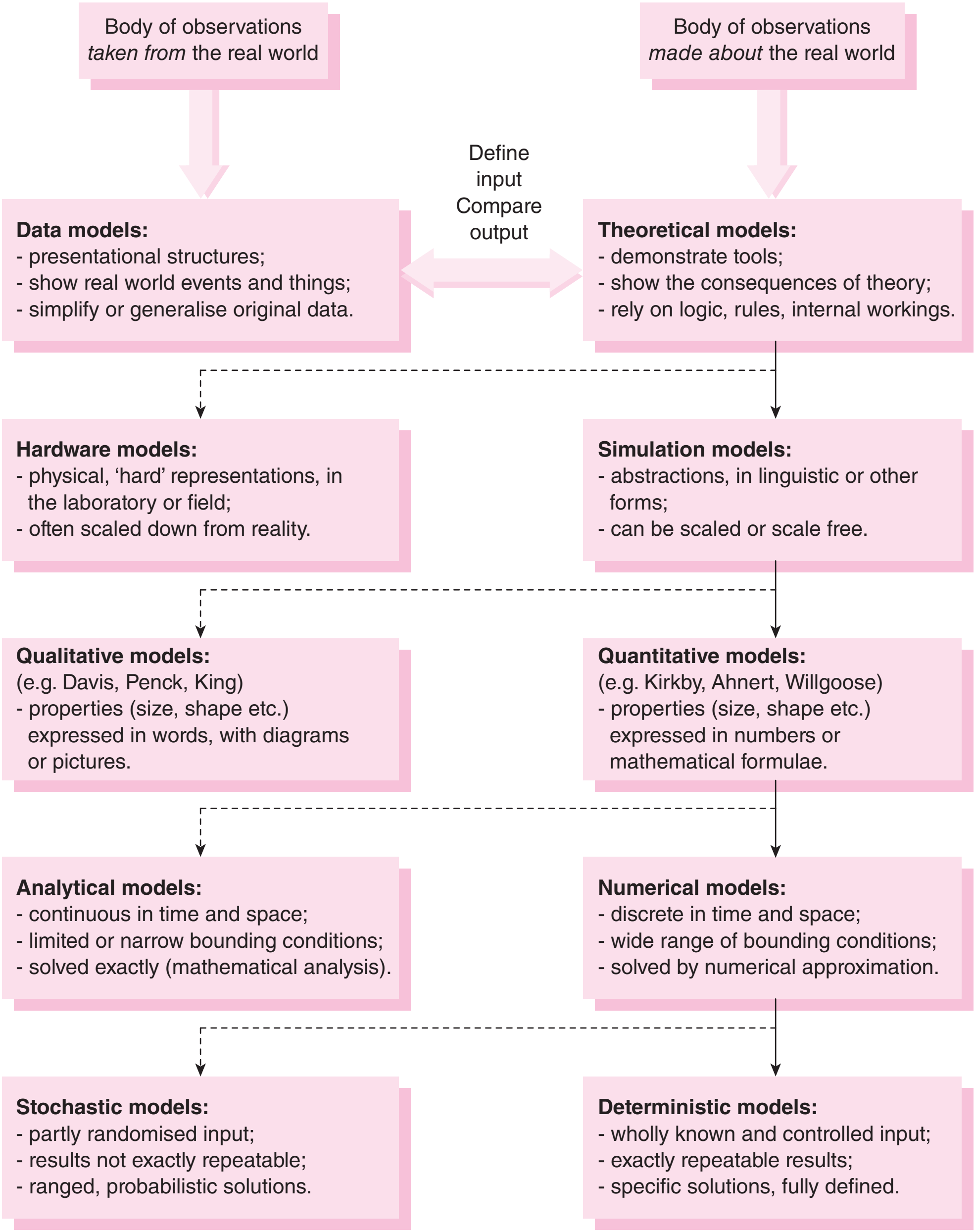

Figure 9.1 A model typology (after Odoni and Lane, 2011: 158)

Table 9.1 Laws of thermodynamics (A simple interpretation of the four laws of thermodynamics attributed to C.P. Snow (Atkins, 2007): the Zeroth law, You must play the game; the First law, You can't win; the Second law, You can't break even; the Third law, You can't quit the game)

Law	Definition	Geomorphic Significance
First	Law of conservation of energy: the total energy of the universe remains constant. The total energy of an *isolated* system remains the same.	All energy transfers must be accounted for, energy can change forms, and energy can flow from one place to another. Continuity equation.
Second	The operation of naturally irreversible processes leads to a decrease in the free energy and an increase in the entropy of an isolated system. Available energy is degraded in any energy transformation process when energy changes into a more dispersed, random or less organized form.	Energy cannot be completely converted into work, systems move towards equilibrium, a state of lower free energy, concentration (storages) of available energy are continuously degraded. See Tables 10.3, 10.4.
Third	The entropy of a system approaches a constant value as the temperature approaches zero.	Systems which use energy best survive.

See Atkins, P. (2007) *Four Laws That Drive the Universe*. Oxford: OUP.

Table 9.2 Newton's laws of motion

Newton's Laws of Motion		
1	An object continues in a state of rest or uniform motion in a straight line unless acted upon by a force; an object in motion remains in motion, and at a constant velocity, unless acted upon by a force.	The laws of thermodynamics (Table 9.1) are the basis for the idea that geomorphic systems evolve to an equilibrium where there is minimum free energy and thus stable conditions.
2	The acceleration of a body is directly proportional to, and in the same direction as, the net force acting on the body, and inversely proportional to its mass. Therefore $\mathbf{F} = m\mathbf{a}$, where $\mathbf{F}$ is the net force acting on the object, m is the mass of the object and $\mathbf{a}$ is the acceleration of the object.	
3	To every action there is an equal and opposite reaction (when one body exerts a force on a second body, the second body simultaneously exerts a force equal in magnitude and opposite in direction to that of the first body).	

Table 9.3 Major categories of earth surface processes

Category of Process	Examples of Force and Resistance	
Exogenetic	**Force**	**Resistance**
Weathering	Crystal growth, heating and cooling, tree roots	Physical and chemical bonding
Mass movement, hillslope processes, including processes of mass wasting	Gravity, increased water content, earthquake movements	Shear strength of materials, binding effects of vegetation, structures
Fluvial, drainage basin processes, hydrologic processes	Gravity, discharge reflecting precipitation, stream power	Friction in fluid and between water and channel margins, obstructions in channel
Coastal processes and landforms that occur on coastal margins	Wave action, tides	Friction on coasts, strength of materials
Aeolian wind-dominated processes in hot and cold deserts and other areas such as some coastal zones	Wind action giving lift force and drag forces	Gravity, particle cohesion, friction between particles and with surface
Glacial, glaciers and ice caps, and landscapes occupied by glaciers, and those glaciated in the past	Gravity, pressure of snow and ice	Friction with bedrock
Periglacial/nival, cryonival, typify the processes in the periglacial zone, in some cases associated with permafrost, but also found in high altitude areas	Expansion of water on freezing	Strength of materials
Subsidence	Gravity following the removal of fluids or material	Strength and cohesion of materials
Soil pedogenic processes, soil erosion	Water and wind on surface	Vegetation cover
Ecosystem dynamics	Animal burrowing	Indurated soils resist plant growth
Endogenetic		
Earthquakes and tectonic	Rock uplift	Gravity, rock strength
Volcanic processes	Magma extruded	Friction with surface

Table 9.4 Some seminal contributions utilizing force and resistance

Contribution, individual and key paper or book	Implication
Grove Karl Gilbert (1843–1918) Gilbert, G.K. (1877) *Report on the Geology of the Henry Mountains*	Now acknowledged to have been a brilliant geomorphologist who made a contribution which anticipated many subsequent developments and whose deductions regarding stream and landscape mechanics inspired quantitative geomorphology in the twentieth century.
Filip Hjulström (1902–1982) Hjulström, F. (1935) Studies of the morphological activity of rivers as illustrated by the river Fyris, *Bulletin Geological Institute Uppsala,* 25: 221–527.	From doctoral thesis published the results of field and laboratory investigations related to the River Fyris and identified relationships between stream velocity, particle size and the processes of erosion, transport and deposition that became of fundamental significance in sedimentology as well as in studies of geomorphologic processes. The *Hjulström* curve is used by hydrologists and geologists to determine the thresholds for erosion or the deposition of particles in flowing water.
Brigadier Ralph A. Bagnold (1896–1990) R.A. Bagnold (1941) *Physics of Blown Sand and Desert Dunes.*	Reviewed bases for underlying processes in desert areas, subsequently working on processes involving fluids other than air, and contributed to the understanding of beach formation by waves based upon wave tank experiments (Bagnold, 1940), to the analysis of fluvial processes (Bagnold, 1960), and finally reviewed fluid flow in general (Bagnold, 1979).
R.E. Horton (1875–1945) Horton, R.E. (1945) Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology, *Bulletin Geological Society of America,* 56: 275–370.	Regarded as a hydrologist who provided the foundation for the Horton runoff model of streamflow generation and a method of stream ordering which gave a basis for the quantitative analysis of land morphometry. Both strands stimulated the greater attention devoted to processes.
A.N. Strahler (1918–2002) Strahler, A.N. (1952) Dynamic basis of geomorphology, *Bulletin Geological Society of America,* 63: 923–37.	Advocated the need for a dynamic basis for geomorphology, endeavouring to extend geomorphology from what is now appreciated to be a functional viewpoint towards a more realist approach. At Columbia University developed a school of geomorphology with many subsequently renowned geomorphologists, including S.A. Schumm (1927–2011), M.A. Melton, M.E. Morisawa (1919–1994) and D.R. Coates, with measurements made of processes operating on stream channel and slopes of a number of areas, later focusing on coastal processes.

(Continued)

Table 9.4 (Continued)

Contribution, individual and key paper or book	Implication
J.F. Nye (1923–) Nye, J.F. (1952) The mechanics of glacier flow, *Journal of Glaciology,* 2: 82–93.	A physicist who derived equations for glacier flow, assuming that ice is a perfectly plastic substance, that it flows down a valley of constant slope, and that the conditions of temperature, accumulation and ablation are simple and uniform.
Ake Sundborg (1921–2007) Sundborg, A. (1956) The river Klaralven: a study of fluvial processes, *Geografiska Annaler,* 38: 127–316.	Results from research on the river Klaralven, Sweden, led to some modification of the relationships produced by Hjulström.
Anders Rapp (1927–1998) Rapp, A. (1960) Recent development of mountain slopes in Karkevagge and surroundings, northern Scandinavia, *Geografiska Annaler,* 42: 73–200.	Study of the mass movement processes on the slopes of Karkevagge (Rapp, 1960) was important not only because it endeavoured to quantify all the processes that affect a slope in a subarctic environment, but also because it established the relative significance of the different processes and concluded that the most effective agent of removal was running water removing material in solution.
J.T. Hack Hack, J.T. (1960) Interpretation of erosional topography in humid temperate regions, *American Journal of Science,* 258: 80–97.	Argued that the concept of dynamic equilibrium provides a more reasonable basis for the interpretation of topographic forms in an erosionally graded landscape, that every slope and stream channel in an erosional system are adjusted to every other, and when the topography is in equilibrium and erosional energy remains the same, all elements of the topography are downwasting at the same rate. In this view the accordant summits in areas like the ridge and valley province of the USA were interpreted as the inevitable result of dynamic equilibrium rather than as remnants of earlier erosion cycles, and this followed from the assumption (Hack, 1960: 81) that 'It is assumed that within a single erosional system, all elements of the topography are mutually adjusted so that they are downwasting at the same rate. The forms and processes are in a steady state of balance and may be considered as time-independent'.

Contribution, individual and key paper or book	Implication
A.E. Scheidegger (1925–) Scheidegger, A.E. (1961) *Theoretical Geomorphology*. Berlin: Springer-Verlag (second edition 1970, third edition 1990)	Conceived his approach from the viewpoint of geodynamics, first book to consider geomorphology within a framework of Newtonian mechanics of earth surface processes and the relation of these mechanistic processes to the physical resistance of earth materials. Did not receive widespread recognition at first but was later acknowledged for providing a theoretical foundation for understanding some geomorphological processes.
Leopold, Wolman and Miller Leopold, L.B., Wolman, M.G. and Miller, J.P. (1964) *Fluvial Processes in Geomorphology*. San Francisco, CA: Freeman.	In 1964 ushered in a new era of process investigations. This book was in effect the first which emphasized contemporary processes and underlying physical principles, and it focused upon river channels, drainage systems, slopes and had some reference to climatic-inspired systems. They contended that process implies mechanics which requires an understanding of the inner workings of a process through the application of physical and chemical principles. After 1964 the need to have a greater emphasis upon processes led to increased familiarity with other disciplines that might indicate the techniques that could be employed for process investigations and empirical measurements, and the content of geomorphology began to show an emphasis upon fluvial geomorphology and hydrology.
J.R.L. Allen Allen, J.R.L. (1970) *Physical Processes of Sedimentation*. London: Allen & Unwin.	A sedimentologist whose 1970 publication demonstrated the foundation for an approach that could be emulated in a geomorphological investigation of processes.
M.A. Carson Carson, M.A. (1971) *The Mechanics of Erosion*. London: Pion. M.J. Kirkby (1937–) Carson, M.A. and Kirkby, M.J. (1972) *Hillslope Form and Process*. Cambridge: Cambridge University Press.	*The Mechanics of Erosion,* later produced *Hillslope Form and Process* with M.J. Kirkby in 1972, advocating a theoretical approach which required an understanding of the physical mechanics of slope development. Contributions by Mike Kirkby have become extremely important in establishing the foundation for understanding geomorphological processes and he initiated the journal *Earth Surface Processes and Landforms* in 1976.
Ian Statham Statham, I. (1977) *Earth Surface Sediment Transport*. Oxford: Clarendon.	Follows a similar approach to Carson (1971) and applies sediment transfer to soils, mass movement, fluids, and then to process regimes and time aspects.

(Continued)

Table 9.4 (Continued)

Contribution, individual and key paper or book	**Implication**
P.J. Williams Williams, P.J. (1982) *The Surface of the Earth: An Introduction to Geotechnical Science.* London and New York: Longman.	Approached geotechnical science with a belief in the need to overcome packaging into 'subjects' and operate within the established principles and laws of the primary sciences of mathematics, physics and chemistry.
J.D. Pelletier Pelletier, J.D. (2008) *Quantitative Modelling of Earth Surface Processes.* Cambridge: Cambridge University Press.	An approach which is founded on theoretical principles, applied to fluvial systems, and extends to non-Newtonian flow equations and stochastic processes.

Table 9.5 Examples of indices used to represent force, resistance, stress and strain in models

Index Used	Explanation	Example of Model Use
Factor of safety (F)	$F = \frac{\sum \text{mobilized resisting forces}}{\sum \text{disturbing forces}}$	
Roughness (Manning's n)	$n = R^{2/3} S^{1/2} / V$	Estimating discharge at ungauged sites
Resistance (Chézy's C)	$C = V/\sqrt{RS}$	ditto
Friction factor (Darcy-Weisbach's f)	$f = 8gRS/V^2$	
Froude number (Fr)	$Fr = V/\sqrt{gD}$	Distinguishes supercritical (shooting) and subcritical (gradually varied) flow
Reynolds number (Re)	$Re = VR/\upsilon$ (where υ is the kinematic viscosity)	Distinguishes laminar (< about 500) from turbulent (> about 2000) flow

Table 9.6 Examples of reasons for increases in shear stress (see Varnes, 1978)

Cause	Specific examples
Loading increased	Natural accumulation of material from upslope Weight of precipitation as snow or rain Seepage pressures of percolating water Human activity such as buildings, piles of material
Removal of underlying support	Undercutting by rivers and waves Solution Mining Removal/squeezing out of underlying sediments
Removal of lateral support, steepening of slope	Erosion by rivers, glaciers, waves Earlier mass movements by falls or slides Weathering or progressive failure Human impact by quarrying, road building
Lateral pressure	Water or ice in cracks Swelling, especially of clays
Transitory stresses	Earthquakes Tree movement in the wind Vibrations due to human impact, explosions

RELEVANT ARTICLES IN *PROGRESS IN PHYSICAL GEOGRAPHY:*

Houser, C. (2009) Synchronization of transport and supply in beach-dune interaction, *Progress in Physical Geography,* 33: 733–46.

Brocklehurst, S.H. (2010) Tectonics and geomorphology, *Progress in Physical Geography,* 34: 357–83.

Bull, L.J. and Kirkby, M.J. (1997) Gully processes and modelling, *Progress in Physical Geography,* 21: 354–74.

Robert, A. (2011) Flow resistance in alluvial channels, *Progress in Physical Geography,* 35: 765–81.