10

GEOMORPHIC WORK

The amount of work done by geomorphic processes is a key geomorphic concept which led to magnitude frequency concepts, followed by power as the rate of doing work. Associated concepts focused upon energy expenditure and usage, including efficiency, entropy, and least work principle, with maximum efficiency at one extreme and minimum power expenditure at the other. Progress of such ideas regarding the significance of energy expenditure developed in the 1960s and 1970s has been the subject of further attention in the 21st century, especially as applied to river systems.

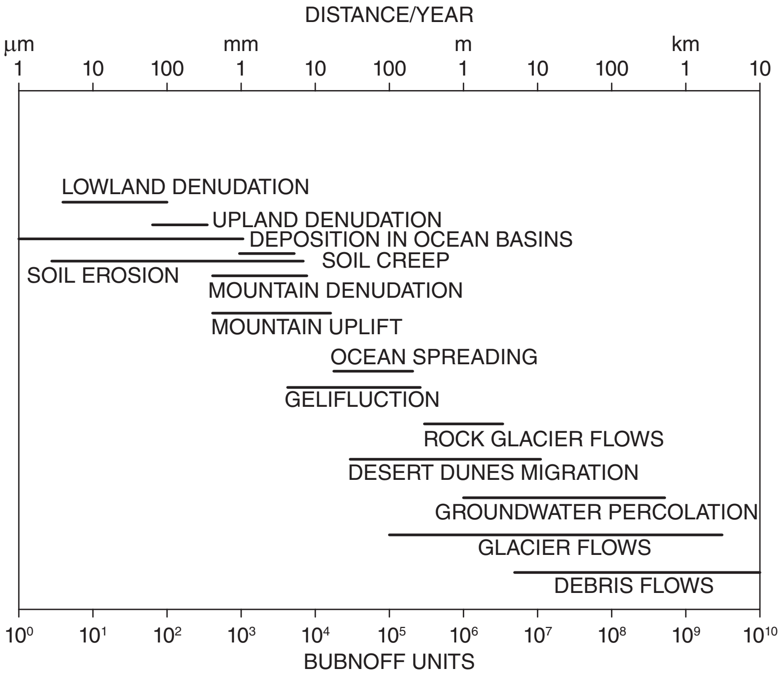

Figure 10.2 Rates of important geomorphic processes (from Smil, 1991, using data from Caine, 1976, and Selby, 1985). A Bubnoff unit is a rate of erosion leading to a loss of 1 mm in 1,000 years equivalent to 1m in one million years

Table 10.1 Examples of research results identifying geomorphic work done

Problem Investigated	Research Results	Source
Relative geomorphic work effected by four processes in rainstorms, a conceptual approach to magnitude and frequency	The difference between the most frequent (modal) events and those which produce the maximum of relative work suggested to depend upon (1) the exponent of the power function, and (2) the dispersion (standard deviation) of the frequency distribution. Presents general model describing the increase of landsliding as a function of event rainfall depth. A four hillslope process model built up with the same assumptions as the model from Wolman and Miller shows that, after a maximum of work by chemical weathering, creep and wash, a new and higher maximum can appear for infrequent slide-triggering rains if they are not very rare and the slopes are sufficiently steep.	Gallar, 1995
Conceptual model of the role of excess energy in the maintenance of a riffle–pool sequence	The geomorphologically effective flow regime used to define temporal balances between riffle and pool energy levels. The geomorphic work carried out by riffles and pools, as described by the excess stream power ($w–w_c$) capable of transporting the bed sediments, displayed a broad balance for the upstream four units before reducing significantly at pool 3 and rising again for the subsequent two units which appear particularly energetic. For sediments to be transferred through a riffle–pool sequence whilst maintaining a quasi-equilibrium form, the pools should carry out the same amount of work as the riffle upstream in order for it not to fill with sediment.	Heritage and Milan, 2004
Weathering, geomorphic work, and karst landscape evolution	Intense, short-duration events dominate in the Cave City groundwater basin, Mammoth Cave, Kentucky. Storms that filled the Logsdon River conduit occurred <5% of the year but were responsible for 38% of the dissolved load leaving the system and from 63% to 100% of conduit growth for various scenarios of sediment influence.	Groves and Meiman, 2005
Evaluation of geomorphic work across flood plains of gravel bed rivers	Present a new and innovative methodology to quantitatively assess the geomorphic work potential necessary to maintain a shifting habitat mosaic for gravel-bed river floodplains. Spatially explicit modelling of water depth, flow velocity, shear stress, and stream power derived from surface hydraulic measurements was combined with airborne multispectral remote sensing for detailed modelling of floodplain water surfaces. Model results combined within a GIS framework to determine potential nodes of channel avulsion that delineate spatially explicit zones across the floodplain where the potential for geomorphic work is the greatest.	Lorang et al., 2005

Problem Investigated	Research Results	Source
Work, persistence, and formative events in relation to the geomorphic impact of landslides	Determine the magnitudes of landslides that impact the landscape in terms of work, persistence, and formative events. A systematic analysis of rapid landsliding indicates that moderate-sized landslides do the most work transporting material on hillslopes. Landslides that form the work peak are distinct from catastrophic landslides that are themselves formative and system resetting. The degree to which an event is individually formative is given by the persistence ratio (PF). Where PF ≥ 10 a catastrophic event has occurred and the geomorphic system has been overwhelmed.	Guthrie and Evans, 2007
Significance of rockfall magnitude and carbonate dissolution for rock slope erosion and geomorphic work	Compare sediment yield, geomorphic work and rock wall retreat of carbonate dissolution and five different magnitudes of rock slope failure in the steep Alpine Reintal trough valley (German Alps). Show that geomorphic work released in the 17.3 km^2 catchment by rockfalls (123 (± 47) W km^{-2}, i.e. 0.38 (± 0.15) mm $year^{-1}$) and solute transport (34 (± 18) W km^{-2}, i.e. 0.05 (± 0.03) mm $year^{-1}$) exceeds previously published Alpine values by one to multiple orders of magnitude.	Krautblatter et al., 2012
Sediment storage and transfer on a periglacial mountain slope (Corvatsch, Switzerland)	Study is the first to include an analysis of the geomorphic work generated on the basis of vertically differentiated sediment production and transport processes.	Müller et al., 2013

Table 10.2 Examples of magnitude and frequency in recent research

Subject	Analysis	Source
Hillslope erosion by rainstorms	Magnitude-frequency analysis by developing Cumulative Erosion Potential (CEP) for Europe and East Africa to provide basis for estimating hillslope erosion by overland flow	De Ploey et al., 1991
Debris supply conditions in predicting debris flow activity	Debris flow frequency and magnitude determined for 33 basins in southwest British Columbia with results stratified into weathering- and transport-limited groups. Provide estimates of debris flow attributes in basins for which few data on past events are available	Bovis and Jakob, 1999
Debris flows on fan	Related large 1996 debris flow in French Alps to magnitude– frequency relationship constructed for last 150 years	Helsen et al., 2002
Landslide magnitude–frequency relation	Quantify the erosion caused by landslides and debris flows in Capilano basin, British Columbia	Brardinoni and Church, 2004
Debris-flow magnitude	Probabilistic analysis of time series from 127 basins in the Eastern Italian Alps provides indications about the relations between magnitude and frequency of debris flows	Marchi and D'Agostino, 2004
Landslide inventories	Using three well-documented landslide events, from Italy, Guatemala and the USA, propose frequency–size distribution for landslides (excluding rockfalls) as useful in quantifying the severity of landslide events and the contribution of landslides to erosion	Malamud et al., 2004
Landslide frequencies	201 debris slides and debris flows analysed in a 286 km^2 area of Vancouver Island, British Columbia, showing average denudation rates of 56 m^3 y^{-1} km^{-2}, examining magnitude–frequency relationships of data set	Guthrie and Evans, 2007
Bankfull discharge magnitude and frequency	Uses 16 gravel-bed river reaches to evaluate several existing methods of determining bankfull discharge and show significance for magnitude and frequency	Navratil et al. 2006

Subject	Analysis	Source
Sinkhole hazard models	Develops methodology that includes the magnitude and frequency relationships of the subsidence process, tested in the Ebro valley in an area where 943 new cover collapse sinkholes inventoried: method could be used to predict the spatial–temporal probability of events with different magnitudes related to other geomorphic processes such as landslides	Galve et al., 2011
Landslide inventories	Study the magnitude and frequency of landslides in relation to climate change	Korup et al., 2012

Table 10.3 Examples of the use of power

Used As	**Application**	**Source**
Critical power	Defined as the power just sufficient to transport the sediment through the reach	Bull, 1979, 1991
Flood power	Related to palaeofloods	Baker and Costa, 1987
Threshold power	For catastrophic modification of the channel or fluvial landscape has been suggested as a unit stream power of 300 Wm^{-2}	Magilligan, 1992
Stream power used in relation to		
Sediment transport	Stream power used instead of stream discharge, velocity or bed shear stress to relate to sediment motion and transport, especially that of bed load	Allen, 1977
River channel patterns	Patterns classified according to amount and size of bedload and stream power; channel sinuosity has been related to stream power	Schumm, 1977, 1981
Urban fluvial geomorphology	Stream power used as unifying theme	Rhoads, 1987
Flood plains	Types of flood plain differentiated according to stream power values, including High energy (ω> 300Wm^{-2}), Medium energy (10<ω>300 Wm^{-2}), and Low energy (ω<10 Wm^{-2})	Nanson and Croke, 1992
Channel morphology	British rivers demonstrated a thousand fold range in the values of specific power with a clear distinction between values of 100 and 1000 Wm^{-2} in the high runoff and steep slope areas of the west, and between 1 and 10 Wm^{-2} in the low slope and low runoff areas of the south and east	Ferguson, 1981
Downstream changes	Downstream changes analysed and shown to be non linear along Wisconsin's Blue River	Lecce, 1997
Stream power along long profiles, Hunter Valley, NSW,	Variability of stream power in headwater reaches is explained by discharge variability, while variability in midstream and downstream reaches is related to high variability in channel gradient	Jain et al., 2006
Flood power, and channel competence of a catastrophic flood in upper Lockyer valley, southeast Queensland	Flood power peaked at 9800 Wm^{-2} along the confined reach and was 2–3 times lower along the unconfined reach: high stream power values, and resultant high erosion rates, within the confined reach are a function of the higher energy gradient of the steeper channel that is associated with knickpoint development	Thompson and Croke, 2013

Table 10.4 Concepts relating to availability or use of energy

Energy	Concept	Definition Explanation	Example of Use
Total amount, potential	Enthalpy	A measure of the total energy of a thermodynamic system	Mathematical model for steady-state regolith production at constant erosion rate (Lebedeva et al., 2010)
Distribution	Entropy	The distribution of energy, the probability of its distribution at a particular time, and a measure of its availability for external work (see Table 10.5)	See Table 10.5
Effectiveness	Efficiency	A level of performance that describes a process that uses the lowest amount of inputs to create the greatest amount of outputs Efficiency is doing things right, while effectiveness is doing the right things	Gilbert (1914) defined stream efficiency = capacity (g/sec)/discharge (cusecs) x percentage slope of channel bed
Expenditure	Minimum expenditure		Yang, 1972
	Minimum energy dissipation rate (mEDR)		
	Maximize sediment transporting capacity		Pickup, 1977 Kirkby, 1977
	Minimum stream power		Yang et al. 1981 Simon and Thorne, 1996
	Least action principle LAP	Nature follows the path that is most 'economical' in terms of work	Nanson and Huang's (2008) least action interpretation of how rivers adjust towards conditions that minimize change and maximize operational efficiency

Table 10.5 Examples of use of entropy in geomorphology

Use In	Interpretation, Analogy to Entropy in Thermodynamic Systems	Source
Geomorphology and general systems theory	An expression for the degree to which energy has become unable to perform work	Chorley, 1962
Landscape evolution	Considered how energy might be distributed and dissipated in the river system	Leopold and Langbein, 1962
Fluvial processes	A measure of the energy in a system available for external work: the greater the entropy, the more energy is ‘unavailable’ for external work	Leopold, Wolman and Miller, 1964
Systems approach	Used very broadly, it is a measure of the randomness of a system organization – the probability of encountering given states, events or energy levels throughout the system	Chorley and Kennedy, 1971
Fluvial geomorphology	Showed that the principle of minimum entropy production rate and the principle that the most probable state of a system is that which corresponds to a maximum of entropy not applicable in stream situations, concluding that the use of entropy as an approach to stream behaviour and sediment transport of dubious validity	Davy and Davies, 1979
Fluvial processes in dryland rivers	Two interpretations are: (a) by analogy with the amount of heat liberated or absorbed by a perfect engine, the available energy in a system declines until the system decays to a state of no available energy which is a maximum of entropy; (b) an alternative interpretation pertains to order and disorder, and as the energy of a system is expended, progressively less is available for work so that disorganization is associated with high entropy values	Graf, 1988
Hillslope sediment production	Equation developed based on physical and probabilistic approaches, allowing the computation of the delivery ratio for every event, considers the physical variables of travel distance, stream power, settling velocity and gross erosion, and solves the probability density function that arises using the principle of maximum entropy	de Araújo, 2007

BOX 10.1

SI units and formulae

Table A.1 SI base and derived units

Physical quantity	Name	Symbol
Base units		
Length	metre	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Thermodynamic temperature	kelvin	K
Amount of substance	mole	mol
Luminous intensity	candela	cd

Derived units	Name	Symbol	Definition	Equivalent form
Plane angle	radian	rad	1	m/m
Solid angle	steradian	sr	1	m^2/m^2
Frequency	hertz	Hz	s^{-1}	
Force	newton	N	$m\ kg\ s^{-2}$	J/m
Energy	joule	J	$m^2\ kg\ s^{-2}$	Nm
Power, radiant flux	watt	W	$m^2\ kg\ s^{-3}$	J/s
Electric charge	coulomb	C	s A	
Electric potential difference	volt	V	$m^2\ kg\ s^{-3}\ A^{-1}$	W/A
Electric capacitance	farad	F	$m^{-2}\ kg^{-1}\ s^4\ A^2$	C/V
Electric resistance	ohm	Ω	$m^2\ kg\ s^{-3}\ A^{-2}$	V/A
Electric conductance	siemens	S	$m^{-2}\ kg^{-1}\ s^3\ A^2$	A/V
Magnetic flux	weber	Wb	$m^2\ kg\ s^{-2}\ A^{-1}$	Vs

Derived units	Name	Symbol	Definition	Equivalent form
Magnetic flux density	tesla	T	kg s^{-2} A^{-1}	Wb/m2
Inductance	henry	H	m^2 kg s^{-2} A^{-2}	Wb/A
Luminous flux	lumen	lm	cd sr	
Illuminance	lux	lx	m^{-2} cd	lm/m^2
Activity of radionuclide	becquerel	Bq	s^{-1}	
Amount-of-substance concentration		M	10^3 mol m^{-3}	

Table A.2 SI prefixes

Multiple	Prefix	Symbol	Multiple	Prefix	Symbol
10^{24}	yotta	Y	10^{-1}	deci	d
10^{21}	zetta	Z	10^{-2}	centi	c
10^{18}	exa	E	10^{-3}	milli	m
10^{15}	peta	P	10^{-6}	micro	µ
10^{12}	tera	T	10^{-9}	nano	n
10^9	giga	G	10^{-12}	pico	p
10^6	mega	M	10^{-15}	femto	f
10^3	kilo	K	10^{-18}	atto	a
10^2	hecto	h	10^{-21}	zepto	z
10^1	deka	da	10^{-24}	yocto	y

Table A.3 Stream velocity formulae

Antoine de Chézy (1719–98)	$V = C\sqrt{Rs}$ (c = 272 for French units; 57.3 for English units)	1775
Pierre DuBuat (1738–1809)	$V = \dfrac{48.85\sqrt{R - 0.80}}{\sqrt{1/S - 1n\sqrt{1/S + 1.6}}} = -0.05\sqrt{R}(\text{pouces } s^{-1})$	1779
J. Eytelwein (1764–1848)	$V = 50.9\sqrt{RS}$	1796
Philippe Gaukler (1826–1905)	$V = \lambda_2 R^{2/3} S^{1/2}$ for $S > 0.0007$	1867

(Continued)

(Continued)

Robert Manning (1816–97)	$V = 62\ S^{1/2}\ (R^{1/2} + R/7 - 0.05)\ (\text{ft s}^{-1})$ $V = 34\ S^{1/2}\ (R^{1/2}\ R/4 - 0.07\ (\text{m s}^{-1})$	1889
“Manning formula”	$V = K\ \dfrac{S^{1/2}R^{2/3}}{n}$ (k= 1 for metric units; 1.486 for English units)	Today

where:

V = mean stream velocity
S = Slope
R = hydraulic radius
C, λ = factors ol flow resistance
n = coefficient of roughness

BOX 10.2

Analogy provided by Wolman and Miller (1960) to illustrate the geomorphic effects of small and moderate events versus extreme events

A dwarf, a man and a huge giant are having a wood cutting contest. Because of metabolic peculiarities, individual chopping rates are roughly inverse to their size. The dwarf works steadily and is rarely seen to rest. However, his progress is slow, for even little trees take a long time, and there are many big ones which he cannot even dent with his axe. The man is a strong fellow and a hard worker, but takes a day off now and then. His vigorous and persistent labours are highly effective, but there are some trees that defy his best efforts. The giant is tremendously strong, but he spends most of his time sleeping. Whenever he is on the job, his actions are frequently capricious. Sometimes he throws away his axe and dashes wildly into the woods, where he breaks the trees or pulls them up by the roots. On the rare occasions when he encounters a tree too big for him, he ominously mentions his family of brothers – all bigger, and stronger, and sleepier.

RELEVANT ARTICLES IN *PROGRESS IN PHYSICAL GEOGRAPHY:*

Boardman, J. (1992) Periglacial geomorphology, *Progress in Physical Geography,* 16: 339–45.

Sharp, M. (1988) Surging glaciers: geomorphic effects, *Progress in Physical Geography,* 12: 533–59.

UPDATES

A further illustration of power (Section 10.3, p. 106) is provided for an analysis of array of geomorphic responses in a river basin in southeastern VT for a short duration high magnitude flood by analysing relationships between geomorphic response and peak stream power, total stream power, and flow duration of stream power above a critical threshold:

Magilligan, F.J., Buraas, E.M. and Renshaw, C.E. (2015) The efficacy of stream power and flow duration on geomorphic responses to catastrophic flooding, *Geomorphololog*y, 228: 175–88.

A long-term field study of two semiarid ephemeral fluvial systems in the Guadalentín basin, SE Spain including analysis of an event with a recurrence interval > 50 years demonstrates the high degree of adjustment of channels to occasional, high magnitude, flash flood events and shows that such events need to be allowed for in management: Hooke, J.M. (2016) Geomorphological impacts of an extreme flood in SE Spain, *Geomorphology*, 263: 19–38.

An investigation of the suitability of map-derived information on total and specific stream power (SSP) to identify erosion, transport or deposition within the channel, showing meaningful patterns between the stream power attributes deriving four classes of reaches according to different sensitivity to erosion and deposition is: Bizzi, S. and Lerner, D.N. (2015) The use of stream power as an indicator of channel sensitivity to erosion and deposition processes, *River Research and Applications*, 31: 1–27.

An analysis of stream power of seven intense flash floods that occurred in mountainous basins of central and southern Europe from 2007 to 2014 shows that values of stream power are generally consistent with observed geomorphic changes in the cross sections studied, bedrock channels show the highest values of unit stream power but no visible erosion, whereas major erosion has been observed in alluvial channels: Marchi, L., Cavalli, M., Amponsah, W., Borga, M. and Crema, S. (2015) Upper limits of flash flood stream power in Europe, *Geomorphology*, (in press).

Least action principle (LAP) in rivers is demonstrated by maximum flow efficiency (MFE). LAP also explains profound biases in Earth's stratigraphic record and provides a new paradigm for river research by identifying the attractor state controlling river channel evolution: Nanson, G.C. and Huang, H.Q. (2017) Self-adjustment in rivers: Evidence for least action as the primary control of alluvial-channel form and process, *Earth Surface Processes and Landforms*, 42: 575–94.