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The physics and chemistry of Earth's dynamic surface (Ralph Alger Bagnold Medal Lecture)

James W. Kirchner
ETH Zürich and Swiss Federal Research Institute WSL, Switzerland (kirchner@ethz.ch)

Ralph Alger Bagnold became a Fellow of the Royal Society and one of the founders of modern geomorphology despite having no formal academic affiliation, no cadre of students or postdocs under his command, no steady financial support, and no scientific training beyond a second-class honors degree in engineering. What he did have, and used to great effect, were a deep curiosity about natural phenomena, a powerful physical intellect, a talent for clever experimentation, extensive opportunities to observe geomorphic processes at work in the field, and – perhaps most important of all – the time and freedom to focus his energies on significant scientific challenges.

A hallmark of Bagnold's work is the artful compromise between the goal of simple, general, physical laws describing natural phenomena, and the practical necessity for observational empiricisms to account for the real-world complexities that cannot be incorporated explicitly into such simple laws. Efforts to find these sorts of artful compromises continue to the present day. Typically, both in Bagnold's work and in present-day geomorphology, one seeks mathematical process laws whose form embodies the "pure physics" of the problem, and whose coefficients subsume the inevitable observational empiricisms.

Present-day geomorphologists have an array of new tools that open our eyes to temporal and spatial scales that were invisible to Bagnold and his contemporaries. These observations, in turn, have yielded new surprises and challenges, sometimes confounding our intuition about how geomorphic systems "should" behave. One surprise has been that decadal-scale erosion rates, as reflected in stream sediment loads and reservoir sedimentation rates, often differ from longer-term erosion rates by large multiples. In some agricultural landscapes, modern-day erosion rates greatly exceed the long-term background rate, as one might intuitively expect. In other landscapes, however, contemporary erosion rates can be a small fraction of the long-term average, suggesting that average erosion rates are dominated by erosional events that are too large or too rare to be captured in present-day measurements.

Recent observations have also spurred new insights into geomorphic process laws. For example, one might intuitively expect that downslope transport rates should be proportional to hillslope gradients, and that as a result, hillslope cross-sections should be parabolic. Instead, cosmogenic nuclide measurements in tectonically active landscapes show that erosion rates increase nonlinearly with hillslope gradients, and hillslope profiles show marked deviations from the expected parabolic form. These observations have motivated a reconsideration of the basic physics of downslope transport, yielding a nonlinear hillslope transport law that is broadly consistent with the hillslope profiles that are observed in steep terrain, and with the observed nonlinear slope-dependence of long-term erosion rates.

The need for artful compromises between pure physics and empiricism is even more evident in current efforts to understand how hydrological, geochemical, and geomorphological processes interact to regulate weathering rates, and thereby long-term consumption of atmospheric CO_2. One might expect that chemical weathering rates should be strongly dependent on the supply of weatherable minerals from physical erosion – or conversely, that physical erosion should be strongly dependent on the weakening of rock by chemical weathering. One might further expect that weathering rates should be strongly dependent on the availability of moisture, and on the temperature-dependent chemical kinetics of weathering reactions themselves. All of these expectations are borne out in field data, but none individually provides a facile explanation for the observed variation in erosion and weathering rates. This lecture will review recent efforts to understand landscape evolution as a coupled physical and chemical process, and to clarify its implications for long-term environmental change.