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Muddying the Waters: Hydrology in Geomorphology

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After my PhD in Cambridge under Dick Chorley in 1963, working on soil creep, I came as a post-doc to America and worked for two years, first with Luna Leopold (USGS) and then with Reds Wolman (TJHU) on catchment hydrology and semi-arid processes, before returning to Britain. There, Dick Chorley pointed me towards the variable source area work of John Hewlett and others, and I became increasingly involved in trying to understand the critical role of water as the key driver, with gravity, of many geomorphological processes. During this period I also began to work with hillslope evolution models, relating the variations in sediment transport rate with slope length and gradient to slope profile development, and the dependence of profile form on the balance of processes acting.

Measurements of throughflow in damp upland Britain during the late 1960s showed that the timing of hillslope hydrographs was almost identical to that of small catchments, although the runoff contribution was commonly lower by one or two orders of magnitude. This work also demonstrated the very strong non-linearity of storm response to rainfall. The eventual outcome of this work was the formulation of TOPmodel, which Keith Beven has so successfully carried forward and evangelised, starting from the work we did together in the 1970s. TOPmodel may be considered as one of a set of fundamental hydrological simplifications, alongside the Unit Hydrograph, the Soliton model for localised storms and models of Hortonian overland flow runoff. The fundamental simplifying assumptions of TOPmodel can be expressed in the form:

1. Subsurface discharge is proportional to topographic gradient

2. Transmissivity is a single-value function of deficit below saturation

3. Runoff and net rainfall are spatially uniform.

Its other properties, particularly the exponential decrease in hydraulic conductivity with increasing saturation deficit, necessarily follow from these. Like other simplified models, TOPmodel assumptions are rarely exactly met, and it is of course sometimes applied in flagrantly inappropriate contexts! However the conceptual simplicity and semi-distributed nature of TOPmodel provided a platform for understanding the partitioning of precipitation between overland and subsurface routes over the landscape, and other concurrent and more recent work has attempted to do the same for infiltration excess flow. These have been my key initial tools for exploring the relationships between water and dirt that is the core of this paper.

This exploration has taken me in a number of directions that criss-cross in a web of interactions that appear to be mutually consistent, but which have never been fully integrated into a single unified model, although containing a number of recurring themes. One theme has been the contrast between humid and semi-arid forms, with their different characteristic processes, vegetation and soils that reflect the dominant modes of hillslope runoff. Subsurface and saturation excess overland flow with strong lateral connectivity are associated with more humid climates and wet seasons; and infiltration excess overland flow and poor connectivity with arid climates and dry seasons. Many places show an alternation between these two modes of flow, shifting seasonally or with spells of exceptional weather. Geomorphological processes follow this dichotomy, with mass movements, solution and soil creep in humid conditions, contrasted with rillwash, gully erosion and lower rates of weathering in more arid conditions, and the regolith and soil horizons reflect this contrast, which, in turn, helps to shape the hydrological response.

The humid/ arid dichotomy is also broadly associated with the contrast between flux-limited and supply-limited removal of material, according to the availability of sediment fine enough to be removed by hillslope and fluvial processes. Where weathering is slower, as in arid areas, or mechanical removal more rapid, as in areas of active tectonic uplift, then the balance moves towards supply-limited removal, influencing river and hillslope morphology and rates of evolution. Hillslope evolution models have been traditionally driven by topographic variables, but a better understanding of the hydrological drivers provides a rational tool for explicitly linking climate and process rate. In principle we can integrate over climate time series, or frequency distributions derived from them, to estimate hydrological response and long term sediment transport rates and how they vary in response to climate as well as topography. This enriches long term evolution models as they allow process rates respond to changes in climate, both due to global drivers and to orography. It also provides an objective basis for looking at spatial variations in, say, soil erosion, over continental areas.

Evolution models rely centrally on the mass balance or continuity equation, and this can equally be applied to model the evolution of the regolith through a balance between mechanical (at the surface) and chemical (at depth) removal. Once more, the role of water flow, both for erosion and in leaching, is critical. In addition the vegetation and soil fauna play a major role in creating soil organic matter and through bioturbation of the soil layers. These processes not only help to drive soil creep, but also establish the bulk density and organic matter profiles that are responsible for the decline in hydraulic conductivity with depth, one of the core components of TOPmodel. In this, as in almost all aspects of the relationship between hydrology and geomorphology, water slowly shapes the morphology of soil and landscape, just as the hydrology is more immediately shaped by landscape form.