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Hydrology beyond closing the water balance: energy conservative scaling of gradient flux relations

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The value of physically-based models has been doubted since their idea was introduced by Freeze and Harlan. Physically-based models like typically rely on the Darcy-Richards concept for soil water dynamics, the Penman–Monteith equation for soil-vegetation-atmosphere exchange processes and hydraulic approaches for overland and stream flow. Each of these concepts is subject to limitations arising from our imperfect understanding of the related processes and is afflicted by the restricted transferability of process descriptions from idealized laboratory conditions to heterogeneous natural systems. Particularly the non-linearity of soil water characteristics in concert with the baffling heterogeneity subsurface properties is usually seen as the dead end for a meaningful application of physically based models outside of well observed research catchments and, more importantly, for an upscaling of point scale flux – gradient relation-ships. This study provides evidence that an energy conservative scaling of topographic gradients and soil water retention curves allows derivation of useful effective catchment scale topography and retention curve from distributed data, which allow successful simulations of the catchment water balance in two distinctly different landscapes.

The starting point of our approach is that subsurface water fluxes are driven by differences in potential energy and chemical/capillary binding energy. The relief of a single hillslope controls the potential energy gradients driving downslope flows of free water, while catchment scale variability in hillslope relief is associated with differences in driving potential energy. It is more important to note that the soil water retention curve characterises the density of capillary binding energy of soil water (usually named soil water potential) at a given soil water content. Spatially variable soil water characteristics hence reflect fluctuations in capillary binding energy of soil water at a given soil water content among different sites. Essentially we propose that a meaning full effective representation of the driving topographic gradient needs to represent the mean distribution of geo-potential energy in a catchment, which leads us to the hypsometric integral. Similarly, we postulate that effective soil water characteristics should characterise the average relation between soil water content and capillary binding energy of soil water. For a given set of soil water retention curve derived from a set of undisturbed soil samples this can be achieved by grouping the observation points of all soil samples, averaging the soil water content at a given matric potential/binding energy density and fitting a parametric relation. We demonstrate that a single hillslope with the proposed effective topography and soil water retention curve is sufficient to simulate the water balance and runoff formation of two distinctly different catchments in the Attert experimental watershed.