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Classification and the role of topography, recharge and boundary conditions on the effects of heterogeneity on subsurface flow in hillslopes

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Distributed hydrologic models based on the Representative Elementary Watershed concept use conservation laws applied rigorously at the scale of landscape elements, but parametrization of the fluxes between the elements is required to provide closure of the governing equations. These ‘closure relations’ cannot be derived by simple averaging of the point-scale process descriptions because of the complexity and heterogeneity of the processes operating within the landscape elements. Some other description that accounts for the effects of the sub-element behavior (without describing them explicitly) is required.

We investigate this problem for the case of flow through the perched saturated subsurface aquifer in hillslopes using an idealized modelof saturated flow based on the Boussinesq equation. We examine the effects of heterogeneity in the hydraulic conductivity and bedrock topography on the details of the internal flow dynamics, and the consequent effects on the hydrologic response at the hillslope scale.

The model results indicate that a range of dynamics and external response modes are possible even in hillslopes with uniform properties, due to the interactions between the boundary condition at the base of the hillslope and the balance of forces driving the internal flow. This balance of forces is shown to be itself dependent on the episodic nature of the recharge, the timescales associated with drainage from the hillslope, and the boundary condition. Using simple scaling relationships, a classification scheme is developed that incorporates the control that the recharge regime and boundary condition have on the hillslope behavior.

It is found that the heterogeneity affects the internal dynamics and response in complex ways, producing power-law like recessions, hysteretic storage-discharge relations, and amplification or damping of peak discharge and storage. In many circumstances the dynamics and hydrologic response have no analogue in hillslopes with ’effective’ uniform properties. Flow paths through the hillslope are found to self-organize into network-like patterns. In certain circumstances, bedrock depression storage disconnects portions of the hillslope, creating a ’fill-and-spill’ phenomenon.

Finally, challenges are identified for the development of closure relations capable of accounting for these effects. A simpler model is proposed that is able to capture many of the effects of heterogeneity by collapsing the full 2-dimensional model into a one dimensional model with a distribution of timescales.