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Analytical upscaling of fill-and-spill hydrology

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Fill-and-spill hydrology, where landscape storage features such as bogs, lakes, prairie sloughs, or surface depressions impound and then dynamically release water after a deficit is filled, has received increased attention in recent years. In systems dominated by fill-and-spill, the contributing runoff area is a function of both local storage deficit and the degree and nature of connectivity between storage features. Here, a closed-form analytical upscaled probabilistic event model of runoff response from thousands of bog cascades in a wetland complex is developed and demonstrated. The efficient mathematical model represents the individual wetland contributing area, runoff coefficient, and pre-event deficit of each bog as probability distributions that may be estimated via a combination of spatial analysis and field observation.

The model is here used to explore the impacts of cascade depth, network branching ratio, local contributing area, and deficit distribution on runoff response. The upscaling results provide insight into the critical runoff characteristics and emergent behaviour of watersheds typified by fill-and-spill hydrology and clarify the role of ‘gatekeeper’ storage features at large scales and for systems with shallow cascade depth. The mathematical solution is found to be a generalization of the well-known PDM (Probability Distributed Model) and Xinanxiang probabilistic runoff models for the specific case where network depth is one and contributing area of each storage feature is zero, and therefore can be readily generalized to support simulation of classical rainfall-runoff responses in heterogeneous landscapes. The results of the model enable exploration of scaling and distribution effects upon catchment runoff in basins influenced by fill-and-spill hydrology.