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Minimum dissipation of potential energy by groundwater outflow results in a simple linear catchment reservoir

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Streamflow recessions of catchments during periods of no recharge can often be reproduced by a simple, linear reservoir despite the complexity of the catchments. Here we show that such a simple linear behaviour can result from the assumption that groundwater drains from smaller units within the catchment into the stream in such a way that the potential energy of groundwater of the whole catchment is dissipated at the minimum possible rate. To do so, we consider the mass balances of groundwater of two connected reservoirs and consider the depletion of potential energy as groundwater drains into the channel network. We show analytically that the depletion of groundwater potential energy of the combined reservoirs has a minimum with respect to a groundwater flux that connects the two reservoirs. The minimisation at the system scale results in equal mean levels of the active groundwater height in the reservoirs in the long-term mean water balance with respect to their channels. These conditions then result in equal relative drainage rates from both reservoirs, which then allow the recession dynamics to be combined into a single, linear reservoir response of the whole system. We then discuss the requirements for such a minimum dissipation state to exist, propose possible mechanisms by which groundwater flow can organise and evolve to such a state, and describe the implications of this outcome for the linear reservoir behaviour and optimisation of catchments more generally. We conclude that the simple, linear response in streamflow recession can be interpreted as the outcome of groundwater flow within the catchment organised to dissipate potential energy at the minimum possible rate. What this implies is that catchments, which appear to be separate units based on the surface topography, may in fact evolve towards a thermodynamic state in which they act more like a unified system, with the linear response in streamflow recession as an outcome. Hence, it would seem that energetic considerations provide an important, additional constraint in the dynamics and evolution of water flow networks within catchments that potentially reduces the problem of equifinality in hydrology.