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Scale invariance of subsurface flow patterns and its limitation

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The morphology of river networks at the Earth's surface has been addressed in numerous studies. Numerical simulations of fluvial erosion processes and concepts of optimization have provided a rather comprehensive understanding about the scale invariance of river networks. Less is known about the structure of preferential flow patterns in the subsurface because these are only accessible by indirect measurements in most cases. As preferential flow patterns are crucial for all transport processes in the subsurface, unraveling their structure is a major challenge in subsurface hydrology. Transferring the idea of optimization from surface flow to subsurface flow it was recently suggested that preferential subsurface flow patterns should also have a dendritic, scale-invariant structure similar to that of river networks.

In this study we analyzed the mean discharges of serval thousand springs with respect to scale invariance. For this purpose we reanalyzed a data set comprising about 17,000 springs from Spain already published in the literature and three new data sets from the Eastern Alps in Austria. We found that the probability density $f(Q)$ of the discharge distribution can be described by a power law with an exponential cutoff,

$$f(Q) \propto Q^{-\tau} e^{-\frac{Q}{Q_c}}.$$

The scaling exponent τ was found to be about 1.6, which is slightly larger than the exponent $\tau = 1.5$ of river networks. In contrast to rivers, the distributions of the spring discharges are characterized by a significant cutoff at large discharges. This cutoff strongly depends on the lithology of the aquifers, while the scaling exponent $\tau \approx 1.6$ seems to be universal. The highest cutoff was found for limestones being one of the primary host rocks for karstic aquifers. We found $Q_c \approx 6000$ l/s for the limestones in the data set from Spain, suggesting a scale-invariant subsurface flow pattern up to catchment sizes of several thousand square kilometers. At the other edge, we found a cutoff at catchment sizes in the order of magnitude of only one square kilometer in the Austrian data sets where the aquifers are primarily located in the weathered zone and debris accumulations of crystalline rocks.