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Anomalous scaling of transfer functions from precipitation to aquifer discharge in Southern Spain explained using a novel multicontinuum approach

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One of the main processes in the basin-scale water cycle is the groundwater recharge from precipitation and the discharge into a river or any outfall. Often, aquifer discharge and precipitation measurements are the only information available when studying the groundwater system of a basin, but this information may be enough to model regional flow, disregarding the details at local scales. The discharge of a catchment is a measure for the recharge at basin-scale, and variations in the discharge represent the dynamic response of an aquifer to changes in recharge.

The ability to understand and model hydrological processes at basin scale is fundamental to improve our ability to manage groundwater resources, predict the effect of large-scale changes in land use and climate. The temporal scaling of discharge is quantified in frequency domain by the transfer function TF, which is defined as the ratio between the spectra of catchment response and recharge time series.

The transfer function may scale with frequency ω as TF(ω) $\sim \omega^{-\beta}$. While the classical linear and Dupuit catchment models predict exponents of $\beta = 2$ and $\beta = 1$, observations indicate scalings with non integer exponents β. In specific, we analyse the hydraulic behavior of fractured formation in Southern Spain, that in a few piezometer display non integer exponent $1/2< \beta <2$. Non integer exponent are commonly model by multi-fractal models, which, however, often lack a relation to the medium characteristics.

The object of this work is to model the aquifer fractal response to precipitation signals with a novel multi-continuum approach [Russian et al. 2013,WRR], which account for the aquifer medium heterogeneity. This multi-continuum catchment model is able to explain non-integer exponent of the frequency transfer function spectrum and link this behavior to a statistical description of the medium heterogeneity. This approach allows to link the fractal dynamics of the discharge process to the physical aquifer characteristics as reflected in the distribution of storage time scales.

The purpose of this work is to apply this new theoretical formulation to explain the anomalous scaling of aquifer response-precipitation signals at the experimental Spanish site, and to built a physical link between soil heterogeneity and mathematical parameters. At this site, precipitation does not follow any specific patterns (uncorrelated structure), the assumption of fractal geometrical distributions of variable flowing regions seems to be physically justifiable and experimental TF can be well fitted by the new proposed model (as they scale like $1/2< \beta <2$). We systematically analyze the catchment responses at the experimental site and we identify and quantify the time scales which characterize the dynamics of the catchment response to recharge.

We conclude that the proposed multi-continuum approach provides a solid solution for long-term prediction of the interaction between precipitation and aquifer responses to recharge, and it is suitable for the analysis and predictions of heterogeneous aquifers, which usually lack of exhaustive direct characterization of aquifer properties.