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Quantifying process heterogeneity: Signal propagation in hydrological systems

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Natural hydrological systems are characterized by heterogeneous structures. The typical length scale of the relevant structures is smaller than the resolution of area-covering methods that are available at the catchment-scale. On the other hand these structures are too large to be treated as random effects and are often related to hydrological behaviour in a non-linear way. Consequently, model results, risk assessments etc. are prone to substantial uncertainties. This is often addressed by random realizations of the structures based on given probability density functions and geostatistical properties, and then analysing the resulting effects on hydrological behaviour, e.g., discharge or groundwater table fluctuations, using process-based models.

In this study an alternative approach was followed. Hydrological systems usually act as low-pass filters: An input signal (precipitation, groundwater recharge, tracer application, etc.) is damped and delayed during its passage through the system. This study aimed at characterizing the damping behaviour in a quantitative way. Large perturbations usually are transmitted at much higher velocities compared to small perturbations, thus hindering a spectrum analysis based approach. Instead, time series of soil water content, groundwater level and catchment runoff from the Uckermark region in North Germany were analysed using a principal component analysis. In all cases, the first component depicted the mean behaviour, and the second component explained a large fraction of the deviations from the mean behaviour. The loadings of the first two components could be used as an index of the mean damping behaviour for the given time period.

Results of the soil water content data showed a linear increase of damping with depth at most sites. However, different sites differed substantially even for backfilled lysimeters that were considered to be homogeneous. There was no clear relationship between clay content and damping behaviour. The analysis of groundwater data showed that pressure signals in a confined aquifer propagated at much higher velocity compared to that in the overlying unconfined aquifer. Hydrographs of adjacent catchments exhibited substantial differences with respect to mean damping of input signals that were related to the fraction of responsive soils in the catchment. To conclude, this approach enabled to assess the effect of subsurface heterogeneities without any information about the internal structure of the hydrological systems. This information will be used to optimize process-based models.