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Measuring and modeling spatio-temporal patterns of groundwater storage dynamics to better understand nonlinear streamflow response

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Information about the spatial and temporal variability in catchment scale groundwater storage is needed to identify runoff source area dynamics and better understand variability in streamflow. However, information on groundwater levels is typically only available at a limited number of monitoring sites and interpolation or upscaling is necessary to obtain information on catchment scale groundwater dynamics. Here we used data from 51 spatially distributed groundwater monitoring sites in a Swiss pre-alpine catchment and time series clustering to define six groundwater response clusters. Each of the clusters was distinct in terms of the groundwater rise and recession but also had distinctly different topographic site characteristics, which allowed us to assign a groundwater response cluster to all non-monitored locations. Each of them was then assigned the mean groundwater response of the monitored cluster members. A site was considered active (i.e. enabling lateral subsurface flow) when the groundwater levels rose above the groundwater response threshold which was defined based on the depth of the more transmissive soil layers (typically between 10 cm and 30 cm below the soil surface). This allowed us to create maps of the active areas across the catchment at 15 min time intervals. The mean fraction of agreement between modeled groundwater activation (based on the mean cluster member time series) and measured groundwater activation (based on the measured groundwater level time series at a monitoring site) was 0.91 (25th percentile: 0.88, median: 0.92, 75th percentile: 0.95). The fraction of agreement dropped by 10 to 15 % at the beginning of events but was never lower than 0.4. Connectivity between all active areas and the stream network was determined using a graph theory approach. During rainfall events, the simulated active and connected area extended mainly laterally and longitudinally along the channel network, which is in agreement with the variable source area concept. However, isolated active parts of the catchment did not connect to the stream during some events. In a sensitivity analysis, we tested the influence of the different groundwater response thresholds and the influence of the uncertainty due to the time series clustering on the extent of the active and connected area. While the size and shape of the active and connected area differed between the scenarios, the dynamics of the connected areas and the relation between storage and streamflow did not differ significantly. This suggests that in steep catchments with shallow perched groundwater tables, groundwater dynamics can be upscaled based on topographic site characteristic to obtain catchment-scale groundwater response patterns, which can then be used to predict the spatio-temporal evolution of the active and connected runoff source areas.