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Integrating water isotopes and cosmic ray sensor data with modelling to understand near-surface storage-discharge relationships in managed landscapes

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Subsurface water storage strongly influences runoff generation processes, regulates agricultural production and defines catchment buffering capacities to hydrometeorological extremes. Knowledge about the amount and spatio-temporal distribution of catchment storage can also be important for constraining and evaluating hydrological models. While it is still challenging to measure this directly, characterisation of catchment-scale storage is more likely to be achieved via a combination of estimation methods at appropriate scales. While stable water isotopes can provide insights into (timescales of) dominant stores and flow paths, novel cosmic ray sensors (CRS) offer insights into large scale water storage dynamics.

Here, we combined stable water isotope analyses with CRS data and rainfall runoff modelling to better understand subsurface storage dynamics and how these relate to catchment runoff generation. We focussed specifically on humid managed environments, such as in NE Scotland, where short-term changes in both storage and management activities occur predominantly at or near the surface. To understand spatial patterns in flow pathways and the evolution of water ages (as mean transit times), we conducted long-term (~5y) stable water isotope monitoring of a nested stream network in a 10km^2 mixed-agricultural catchment. Monitoring also involved artificial drains of agricultural fields and country roads. This was complemented with a short-term study (~14 months) of mobile soil water in key soil-land use units. Additionally, we characterised field scale near-surface storage dynamics in these same key soil-land use units using CRS technology. Finally, we explored the storage-discharge relationships based on these CRS storage estimates and the information content of these novel data for rainfall-runoff model calibration to better characterise catchment-scale storage dynamics.

The outcomes of both transit time and rainfall-runoff modelling highlighted the importance of near-surface storage dynamics for catchment functioning and streamflow generation. Predominantly young waters (<1 y) across the stream network were associated mainly with shallow soils and the extensive artificial field drainage, which short-circuits water delivery to the

streams, especially during wet periods. Water ages in soil mobile water were also short (1 – 6 months) and subtle differences between the key soil-land use units were associated with land management practices, which either enhanced (artificial drainage, ploughing) or delayed (compaction) transit times in the soil. As CRS near-surface storage estimates related well to catchment scale storage dynamics (R^2=0.91) and stream discharge (R^2=0.71), we evaluated the effect of using CRS data in model calibration. Including it in the model calibration was especially useful during intermediate and wet periods. Overall, our results showed that a combined model calibration using discharge and CRS estimates provided a better representation of catchment internal dynamics, additionally reducing uncertainty during low flows.

In the context of a humid managed catchment, our results showed that the integration of water isotope analyses and CRS-derived storage estimates can provide unique insights into catchment scale sub-surface storage dynamics, runoff generation and the evolution of water ages in soils and streams. They also demonstrated the potential of these data for informing rainfall-runoff modelling frameworks, but further work is needed across a range of different environments to explore wider applications.