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Visualizing catchment-scale spatio-temporal dynamics of storage-flux-age interactions using a tracer-aided ecohydrological model

Aaron Smith[1] | Doerthe Tetzlaff[1,2,3] | Marco Maneta[4] | Chris Soulsby[2,3]

[1]Department of Ecohydrology and Biogeochemistry, IGB Leibniz Institute of Freshwater Ecology and Inland Fisheries Berlin, Berlin, Germany

[2]Geographisches Institut, Humboldt University Berlin, Berlin, Germany

[3]Northern Rivers Institute, School of Geosciences, University of Aberdeen, Aberdeen, UK

[4]Department of Geosciences, University of Montana, Missoula, Montana, USA

Correspondence
Aaron Smith, Department of Ecohydrology and Biogeochemistry, IGB Leibniz Institute of Freshwater Ecology and Inland Fisheries Berlin, Berlin, Germany.
Email: smith@igb-berlin.de

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1 | DESCRIPTION

Quantifying catchment-scale water cycling over longer periods is important as wet and dry precipitation cycles can adversely affect blue (groundwater and discharge) and green (evapotranspiration) water fluxes and storage dynamics (Orth & Destouni, 2018; Yang et al., 2021). Spatially distributed modelling approaches are, in many circumstances, essential for spatio-temporal evaluation of the non-stationarity of flow paths and storage dynamics within catchments (Fatichi et al., 2016). When linked with tracers and water age tracking, such models can also aid in understanding the ecohydrological separation of water sources (McGuire & McDonnell, 2015). Here, we present a visualization of results from a tracer-aided ecohydrological model to explore spatiotemporal dynamics of water flux-storage-tracer-age interactions through wet and extreme dry cycles (including the European 2018 drought). This visualization extends beyond the traditional "snapshot" of spatial catchment conditions or temporal depiction of a single "point", aiding more rapid identification of key ecohydrological regions for changes in flux-storage interactions, as well as tracer dynamics and water ages during periods of specific interest (visualization time-stamps). Intrinsically, the visualization provides a further novel understanding of spatial differences in catchment response and interactions under wet and dry conditions. Importantly, the application of such visualization approaches are limited only by model outputs, and the visualization results presented here are shown for a catchment with broadly similar soil and land use characteristics of extensive parts of the North European Plain and at a scale where process aggregation is lessened (Smith et al., 2021).

EcH$_2$O-iso is a tracer-aided ecohydrological model coupling vegetation-soil-atmosphere energy, water and tracer mass-balance with a simultaneous solution of vegetation dynamics and water age (Kuppel et al., 2018; Maneta & Silverman, 2013). Energy and water balance are estimated with a top-down approach from the canopy to the sub-surface. The energy balance is solved iteratively for temperature (canopy and surface) to estimate latent, sensible, and ground heat, soil temperatures and net radiation. Water balance is solved in five model storages: canopy, surface and soil (three storage layers) with vertical movement through all storages, and lateral movement (kinematic wave) in surface and deep soil water. Evapotranspiration components are derived from the energy balance. Water ages and isotopic tracers are estimated in each storage with complete mixing. The Demnitzer Millcreek catchment (DMC, 66km^2) is a mixed-land use mesoscale catchment in north-east Germany. The DMC has annual mean precipitation and discharge of 560 and 60 mm, respectively with stream flow being groundwater-dominated (Smith et al., 2020; Smith et al., 2021). Four major land use units are distinguishable: agricultural, coniferous forest, wetlands and broadleaf forest. The soils are primarily sandy brown earths, with peaty podzolic soils in wetlands and peaty gleys fringing the channels. Discharge and stream chemistry time-series (1990–present) and soil moisture, sap flow, soil and discharge isotopes (2018-present) have been monitored in the main channel and primary land uses (Gelbrecht et al., 2005; Smith et al., 2021). EcH_2O-iso was set up on 250 m square grids for the DMC and simulated on daily time-steps from 2007–2019 using the first two years as spin-up. Multi-criteria calibration utilized data available across the catchment including soil moisture (0–1 m), stream discharge, sap flow, latent heat and soil, groundwater and stream isotopes to constrain soil storage, ecohydrological fluxes and isotopic tracers in the primary land uses (nine soil and six vegetation parameters for each land use, Smith et al., 2021). Calibrated soil parameters include Green-Ampt model parameters (four parameters), groundwater seepage to the channel, soil anisotropy, soil depth, Manning's and soil albedo; while vegetation parameters included stomatal conductance parameters (maximum, and light and VPD parameter sensitivity), canopy water storage, root distribution, and light attenuation coefficient (Smith et al., 2021). Calibration revealed a relatively well constrained model with Nash-Sutcliffe Efficiency (NSE) > 0.5 for stream water, and NSE reaching ~0.4 for soil moisture and latent heat across the catchment, and low normalized root mean square error (NRMSE) for isotopic datasets (0.01–0.05).

The visualization (Movie S1) shows spatially distributed bi-weekly average changes in catchment storage (in shallow soil and groundwater), transpiration, specific discharge, transpiration and discharge age, and tracer dynamics (shallow soil and discharge) over an extended period from 2009 to 2019 to provide novel insights into spatially disaggregated catchment interactions in wet and dry periods. The visualization was created by translating portable network graphics (PNG) into an audio video interleave (AVI) at four frames per second using Matlab®. The bottom left panel shows the profile of catchment land use for context, with agriculture dominant in the north, wetlands in the central catchment and forests in the south. To aid in spatial visualization, the scales are set to the 5th and 95th percentiles of monthly averages, with a log-scale for the transpiration ages. Low precipitation toward the end of the study period caused a long-term decrease in groundwater (meters of water above field capacity) and summer soil water storage and an increase in transpiration age.

Relationships of catchment wetness to storage, fluxes, tracers, and ages were temporally consistent; however, the strength of these relationships changes seasonally. Higher wetness conditions during the early and mid-growing season (0:07 and 0:21) decreased total catchment transpiration relative to drier years (0:39 and 0:43) due to lower atmospheric vapour pressure deficit in the canopy as well as greater energy usage for interception evaporation (decreased energy available for transpiration) in wet conditions. Wetter conditions increased soil water fractionation (higher δ^2H) during the early and mid-growing season due to increased soil evaporation where VPD at the surface was not as low as in the canopy. Late growing season wetness conditions did not strongly affect transpiration; however, wetter conditions in winter and higher rainfall years resulted in an inverse storage effect showing increased discharge and decrease water ages of transpiration and discharge as the water velocity in near-surface flow paths increased (0:09 vs. 0:57).

Spatio-temporal differences between wet and dry growing season months are primarily distinguishable by land use. In particular, wetlands consistently had higher moisture and lower transpiration, while spatial differences between agricultural areas in the north and conifer forests in the south deviated with wetness conditions. Wet conditions in the early growing season reduced spatial differences of soil moisture (e.g. 0:26 vs. 1:01) due to relatively similar soil types and similar vegetation water use, but resulted in larger spatial differences in stream water age (younger water age through the conifer areas), and decreased spatial differences in transpiration water age between conifers and agricultural areas. Spatial differences in soil moisture were not as prominent during the mid-growing season regardless of wetness conditions. However, wetter conditions in mid-summer drove greater spatial differences in transpiration and channel fractionation, and lower differences in transpiration age between conifers and agricultural land use (e.g. 0:50 vs. 0:38). Larger differences in transpiration age during dry conditions (older in conifers) suggest the resilience and capabilities of such vegetation to draw from deeper, older soil stored water and has significant implications in reducing available blue water stores within the catchment. Under these conditions, transpiration rates were higher in conifer forests, and more water available in shallow soils for transpiration spatially unified water ages throughout the catchment. Drier conditions resulted in lower transpiration in conifer forests compared to agricultural areas. Spatio-temporal variations during the late growing season showed further consistent trends with wetness, with greater spatial differences in transpiration and smaller spatial effects of channel fractionation under wetter conditions (0:15 vs. 0:45).

Here, we explored the visualization of spatio-temporal dynamics catchment fluxes, storages, tracers, and water ages through wet and dry periods in a mesoscale, mixed-land use catchment in Germany. Spatial variation in transpiration, evaporative fractionation, water age and soil moisture are directly related to inter-annual variations of catchment wetness, with additional intra-annual spatial variability within the growing season. These visualizations of storage-flux-age dynamics aid in the understanding of the sensitivity of key catchment regions and could improve knowledge of hydrological catchment functioning in wet and dry conditions under long-term change. As such, they are useful tools to communicate the output of complex ecohydrological models to land managers and could form the basis for interactive tools to assess environmental change scenarios.

DATA AVAILABILITY STATEMENT

The data used are available from the corresponding author upon request. The model code of EcH2O-iso is publicly available at http://bitbucket.igb-berlin.de:7990/users/ech2o/repos/ech2o_iso/ (last access: December 2021).

ORCID

Aaron Smith https://orcid.org/0000-0002-2763-1182
Doerthe Tetzlaff https://orcid.org/0000-0002-7183-8674
Chris Soulsby https://orcid.org/0000-0001-6910-2118

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

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