

Impact of antecedent wetness and precipitation intensity on catchment travel and response times

Julia L. A. Knapp^{1,2}, Wouter R. Berghuijs^{2,3}, Jana von Freyberg^{2,4,5}, and James W. Kirchner^{2,5}

¹ Department of Earth Sciences, Durham University, United Kingdom

² Department of Environmental Systems Science, ETH Zurich, Switzerland

³ Faculty of Science, Earth and Climate, Vrije Universiteit Amsterdam, The Netherlands

⁴ School of Architecture, Civil and Environmental Engineering, EPFL, Lausanne, Switzerland

⁵ Swiss Federal Institute for Forest, Snow and Landscape Research, Switzerland



Background

Here we investigate how **response times** (the time discharge takes to respond to rainfall inputs, i.e. celerity) and **travel times** (the time a molecule of rain takes to reach the stream, i.e. velocity) are affected by **precipitation intensity** and **antecedent catchment wetness**.

Data

3 years of hourly water fluxes (P,Q) and water isotope data from **Erlenbach**, a steep pre-alpine headwater catchment in Switzerland.

1 year of 7-hourly water fluxes (P,Q) and water isotope data¹ from the **Upper Hafren**, a moorland catchment in Wales.

Analysis

The time series were segregated by ranges of precipitation intensity (PI) or antecedent wetness (AW). We then calculated new water fractions using ensemble hydrograph separation^{2,3} and ensemble rainfall-runoff analysis for different combinations of PI and AW: AW_{low} & PI_{low} ; AW_{low} & PI_{high} ; AW_{high} & PI_{low} ; AW_{high} & PI_{high} . These analysis approaches assess (average) response times and travel times for whole subsets of data rather than individual storm events.

We quantified (see Fig 2 a&b):

- the response time of streamflow to precipitation
 - the runoff coefficient (Q/P)
 - backward new water fractions $Q_p F_{new}$
 - forward new water fraction $P F_{new}$
- at different combinations of AW and PI.

Results

Travel times vs. response times

The discharge response to rainfall is **much quicker and substantially stronger** than the travel time distribution.

Combined effects of antecedent wetness and precipitation intensity on...

- the rainfall-runoff response:
During more intense precipitation and/or wetter catchment conditions
 - The peak height is greater and the signal more pronounced at early lags
 - The response happens more quickly
 - The runoff coefficient (Q/P) increases→ **more rapid, less dispersed response, more water is mobilized**
- new water fractions:
At more intense precipitation and/or wetter catchment conditions
 - both forward and backward new water fractions generally increase.
 - $P F_{new}$ (fwd Fnew) is high if *both precipitation intensity and antecedent wetness* are high.
 - $Q_p F_{new}$ (bckwd Fnew) is mostly high if *precipitation intensity* is high.
 - Higher antecedent wetness alone is not sufficient to promote rapid transport.→ **The relative amount of recent precipitation in the stream increases, a larger portion of precipitation is routed to streamflow.**

Both response and travel times have been quantified in the past. Here we combine their analysis to improve our understanding of how catchments store and release water at different catchment conditions. Can we use these techniques to quantitatively assess flowpaths directly from data?

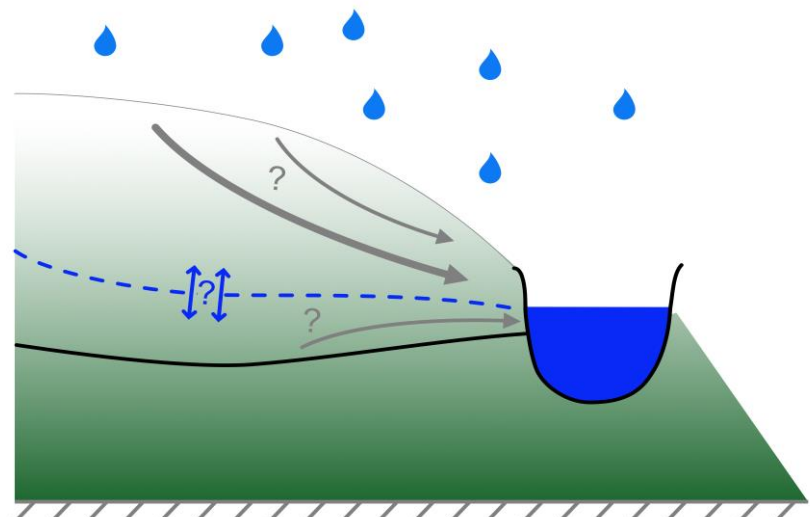
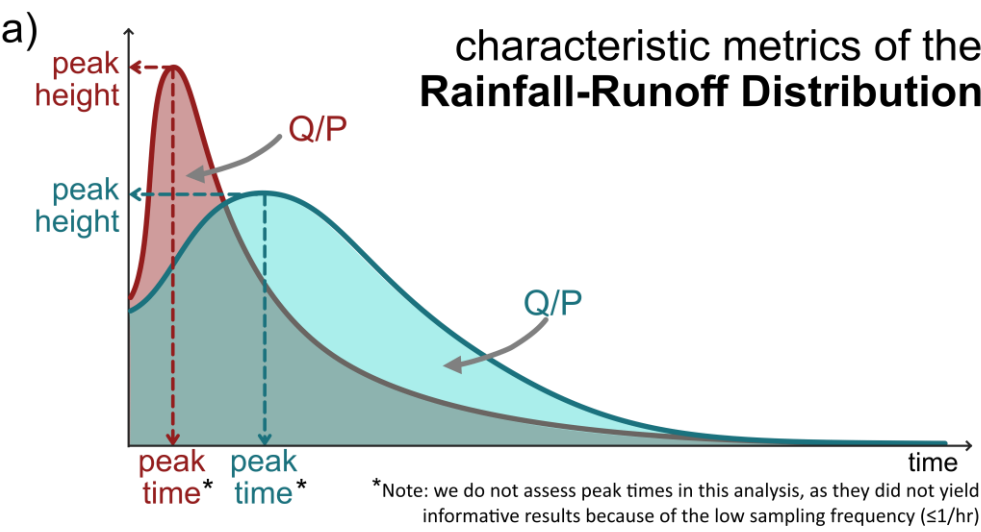


Fig 1: Precipitation intensity and antecedent wetness affect how water is stored in and transported through the catchment. We aim to quantify these effects better by combining the assessment of response times and travel times.

characteristic metrics of the Rainfall-Runoff Distribution



Travel Time Metrics

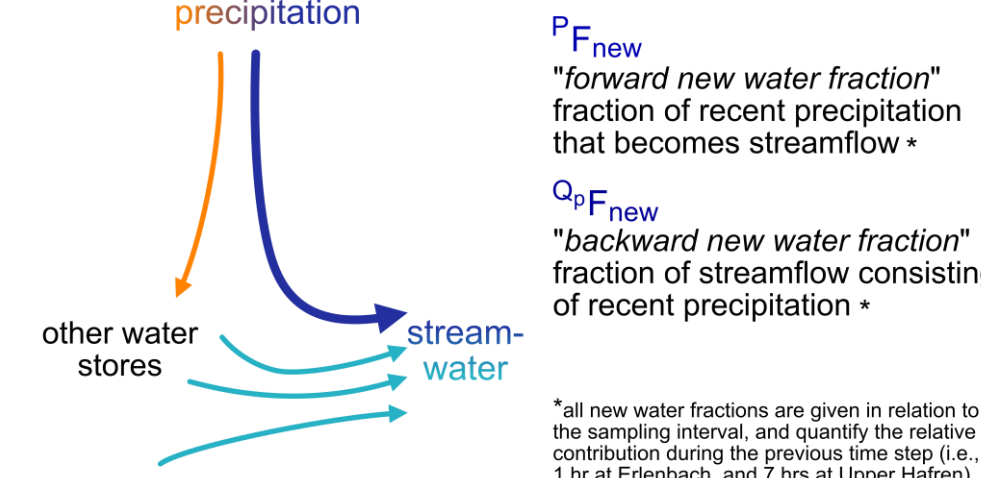


Fig 2: An illustration of the characteristic metrics of the ensemble rainfall-runoff analysis (a), as well as travel time metrics determined from natural tracer time series (b).

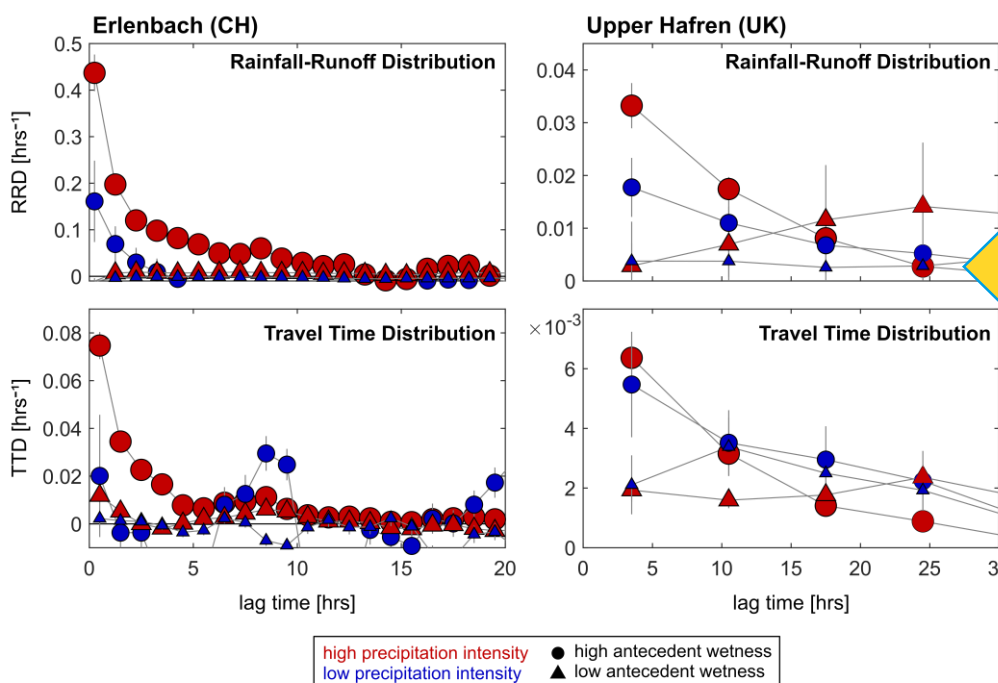


Fig 3: Effect of antecedent wetness and precipitation intensity on rainfall-runoff responses (top) and travel time distributions (bottom). TTDs are substantially smaller than the RRDs (by approximately a factor of 5 at both sites). Fastest rainfall-runoff responses and travel times are obtained for intense precipitation onto a wet catchment (red circles). Low intensity rainfall and dry catchment conditions neither result in a fast runoff response nor fast transport (blue triangles). High precipitation intensity in case of dry catchment conditions (red triangles), however, appears to deliver recent precipitation to the stream, although the rainfall-runoff response is around zero.

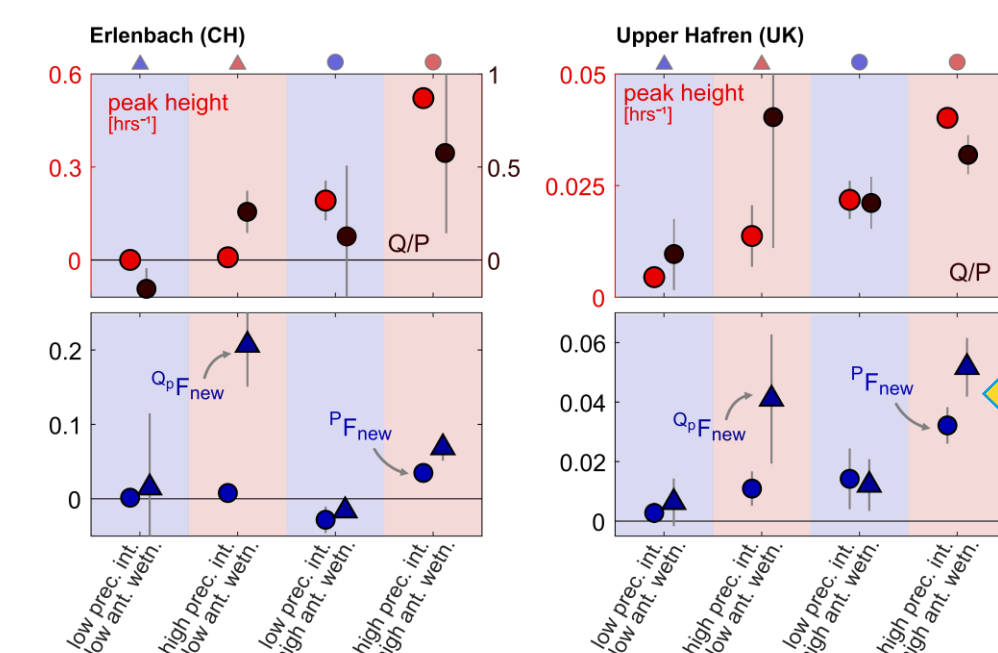


Fig 4: Effect of antecedent wetness and precipitation intensity on peak heights and runoff coefficients (top), as well as new water fractions (bottom). Peak height, runoff coefficients, and new water fractions increase as precipitation intensity increases and/or the catchment becomes wetter, indicating stronger (and likely faster) propagation of pressure and water through the system. There are some differences between the Erlenbach and Upper Hafren, e.g. with respect to the magnitude of the response and travel times, but the general behaviour across conditions is relatively consistent between the two sites. This allows quantifying the amount of infiltration and subsurface flow in different catchment settings. The background shading and the symbols above the top figure are intended to allow easier allocation of the metrics in this figure to the distributions in Fig. 3.

1 The discharge response to rainfall is much faster and substantially larger than the transit time distribution
→ here, celerity is around five times faster than velocity

2 Combining information from response time and travel time analysis enables a better system's understanding regarding how catchments store and release water.

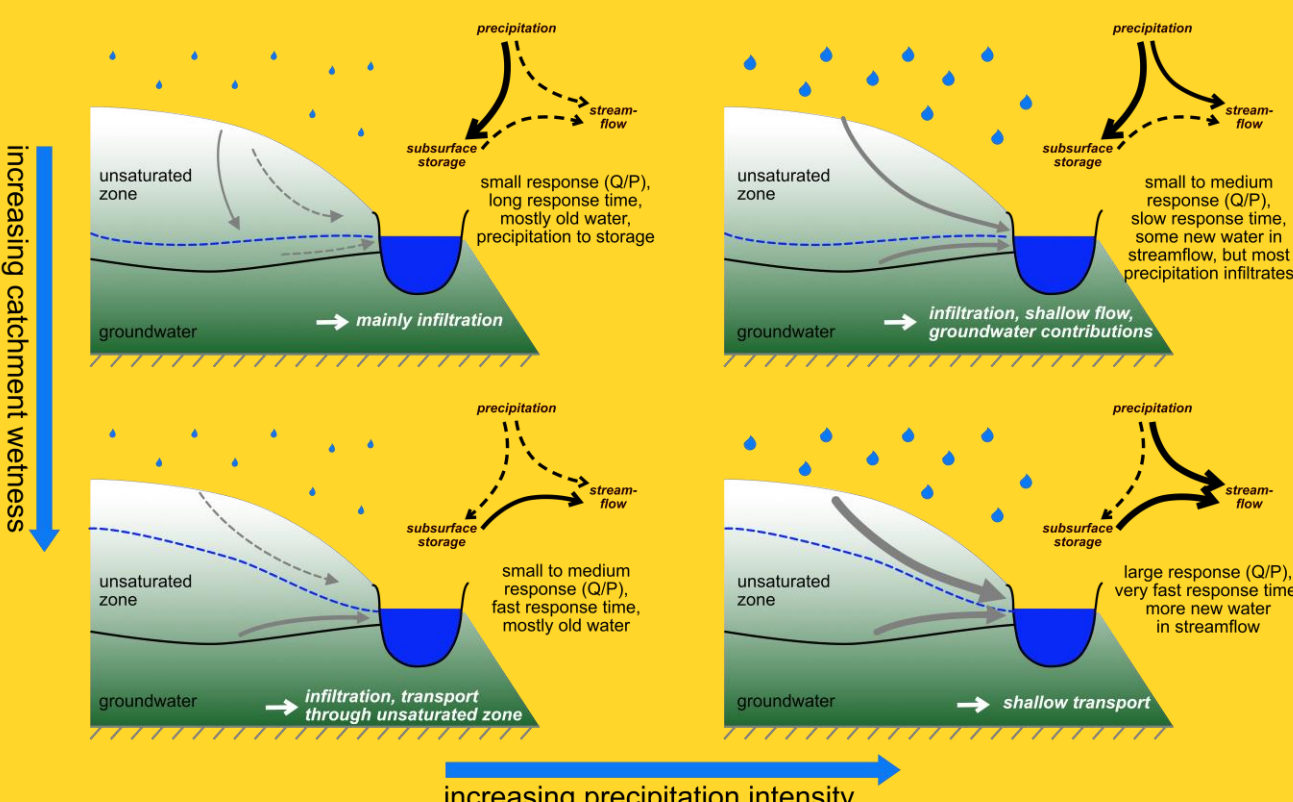


Fig 5: Storage and release of water at high/low precipitation intensity and dry/wet catchment conditions as derived from metrics of rainfall-runoff and travel time analyses. The three arrows at the top right of each panel give a qualitative indication of the most relevant processes.

References

- (1) Knapp, Neal, Schlumpf, Neal, & Kirchner (2019): [New water fractions and transit time distributions at Plynlimon, Wales, estimated from stable water isotopes in precipitation and streamflow](#). *Hydrology and Earth System Sciences*, 23(10), 4367-4388.
- (2) Kirchner (2019). [Quantifying new water fractions and transit time distributions using ensemble hydrograph separation: theory and benchmark tests](#). *Hydrology and Earth System Sciences*, 23(1), 303-349.
- (3) Kirchner & Knapp (2020). [Technical Note: Calculation scripts for ensemble hydrograph separation](#). *Hydrology and Earth System Sciences*, 24(11), 5539-5558.

[click to view the paper!](#)

Questions, feedback, comments? Email me!

julia.l.knapp@durham.ac.uk

