Implications of an “inverse storage effect" (ISE) on the sensitivity of watershed transit times to rainfall variability at Plynlimon, Wales

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What was our motivation?

- The dynamic flow pathways of a watershed result in a time-varying, probabilistic distribution of water-parcel transit times called the transit time distribution (TTD).
- TTDs are important aspects of contaminant transport at the catchment scale (McGuire & McDonnell, 2006).
- The shape of the TTD generally depends on the history of rainfall over a watershed, which may shift substantially under a changing climate (Walsh et al., 2014).
- Harman (2015) recently described a generalized means of simulating TTDs using rank StorAge Selection (rSAS) functions that is well-suited for studying the dependence of time-varying TTDs on rainfall variability.
- Harman applied the rSAS model to the Plynlimon research catchment and observed an “inverse storage effect” (ISE), in which times with *higher* catchment storage anomalies were associated with *lower* catchment transit times (Harman, 2015).

What were the research questions?:

- How sensitive are catchment TTDs to the amount and pattern of rainfall?
- How does the presence or absence of an “inverse storage effect” affect the sensitivity of catchment TTDs to the amount and pattern of rainfall?
- To what extent could watershed TTDs be altered by changes in the mean intensity and pattern of rainfall due to climate change?

These questions are explored with a case study in a research catchment.

Where is the study site?

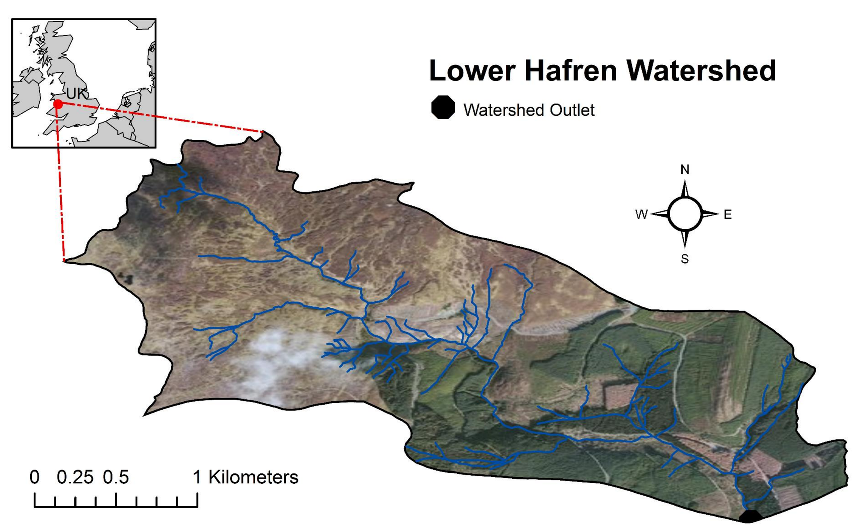


Figure 1: Lower Hafren watershed. A 2.7 km^2 research catchment with an extensive, multi-decadal, publicly available record of monitoring data (Neal, Kirchner, & Reynolds, 2013).

What is the rank Storage Selection (rSAS) function transport model?

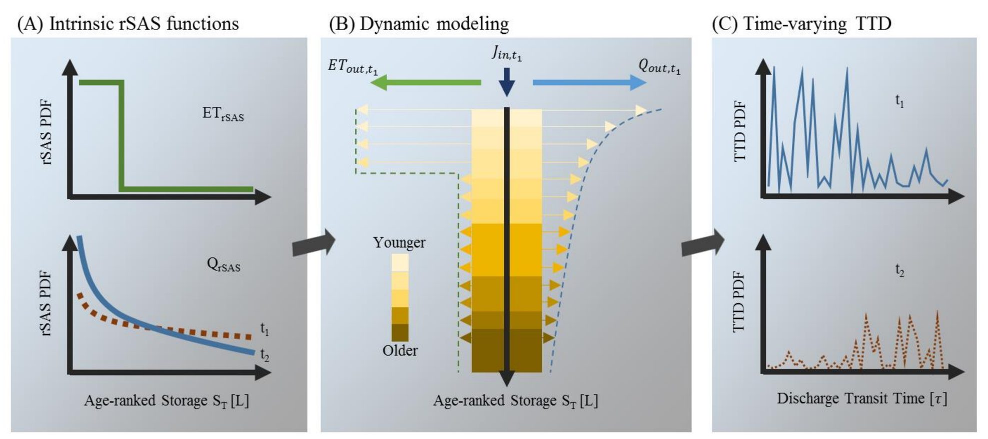


Figure 2. Illustrative overview of the rSAS model. The model uses climatic inputs and a parameterized rSAS function to simulate time-varying TTDs. Panel A shows rSAS functions, which are the probability distribution of storage ranked by age. Panel B shows the rSAS function acting on the age ranked storage to determine the water ages that are “selected” into discharge. Panel C shows the resultant time-varying TTDs. Conceptualization adapted from Harman 2015.

How did we conduct our model sensitivity study?

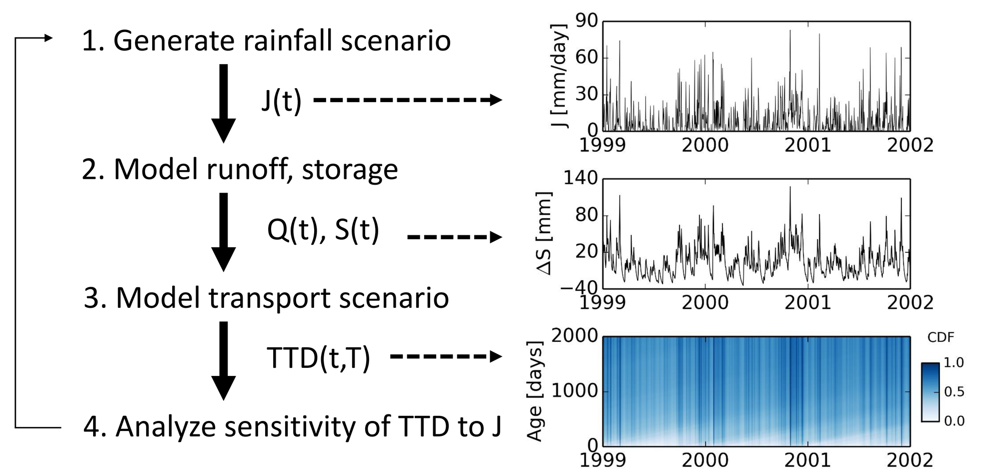


Figure 3. Simplified workflow. Rainfall J(t) scenarios were developed using observations (1983-2008), a synthetic rainfall generator, and downscaled climate projections. Runoff and storage anomaly were estimated using a simple storage discharge model. Transport was modeled with the rSAS transport model (see figure 2) calibrated to chloride tracer data using methods described elsewhere (Harman, 2015). Various statistical techniques were used to tease out the association between rainfall patterns and TTDs.

What were the rainfall scenarios?

Figure 4 (upper right). Examples of synthetic rainfall scenarios. Historic observations were used to parameterize a rainfall generator (see summary including calibration procedure in Robinson & Sivapalan, 1997). The figure shows how the parameters of the generator could be adjusted to simulate different rainfall patterns.

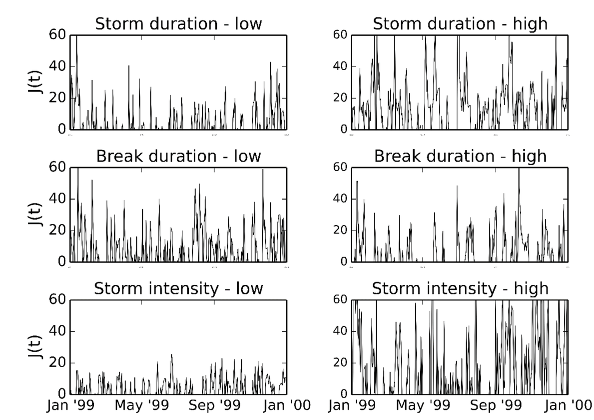
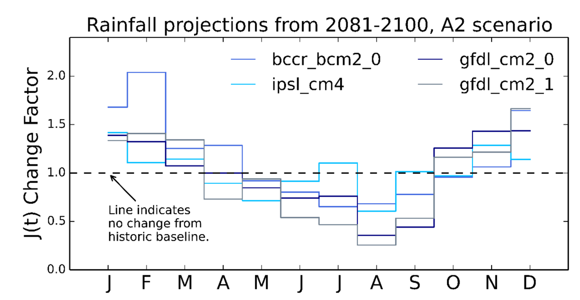
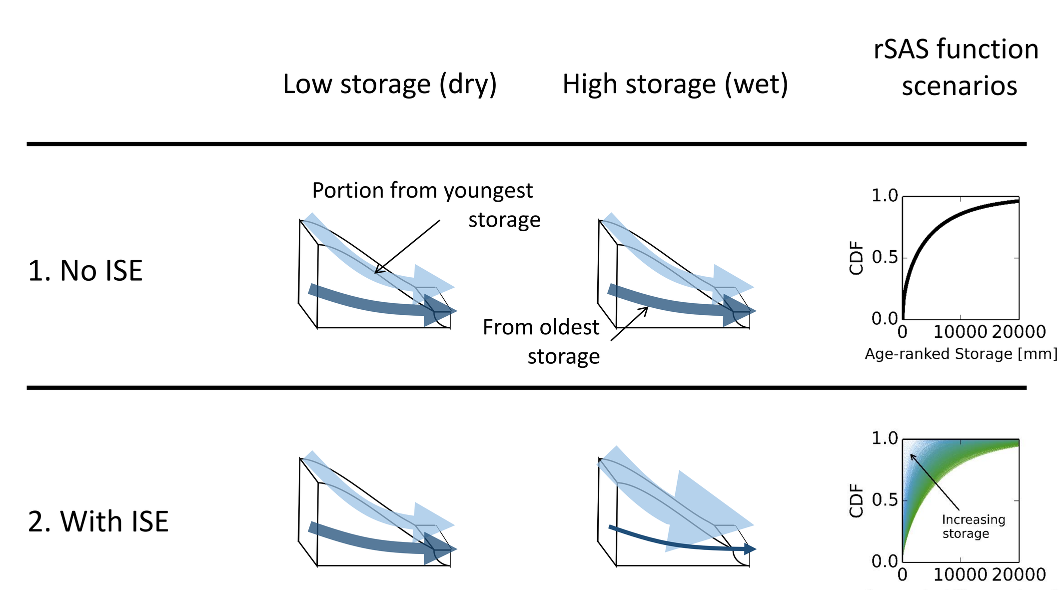


Figure 5 (lower right). Climate change scenario change factors. These multiplicative factors were derived from downscaled CMIP3 GCMS (source:http://sdwebx. worldbank .org/ climate portal/) and used to project rainfall using the delta change method (Hay et. al, 2011).



What were the transport scenarios?



Result 1: The coupled modeling experiment did well at simulating historic rainfall, runoff, and transport.

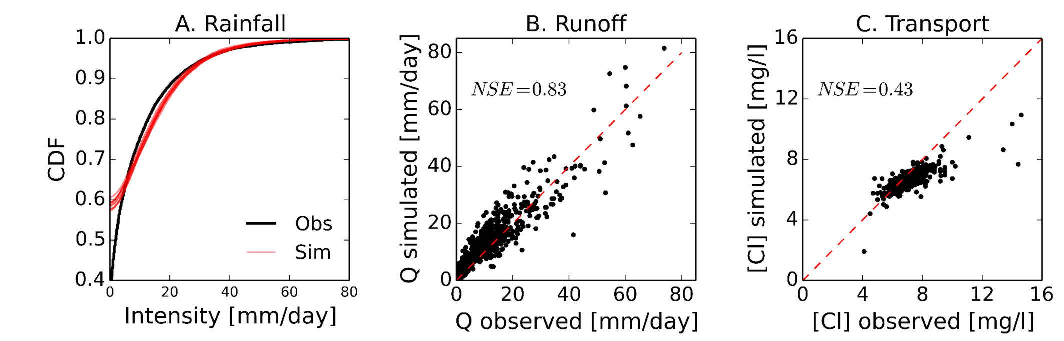
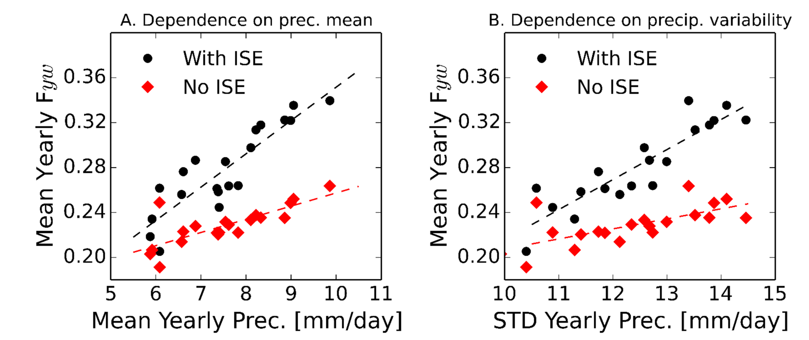


Figure 6. Model calibration results. Parameter calibrations generally involved minimizing the RMSE between observations and simulations using a minimization routine with SciPy 0.16.0. Panel A shows one of several metrics that showed good agreement between simulations (Sim) with a rainfall generator and historic rainfall observations (Obs). Panel B and C shows the ability of the models to reproduce runoff and transport of the conservative tracer chloride.

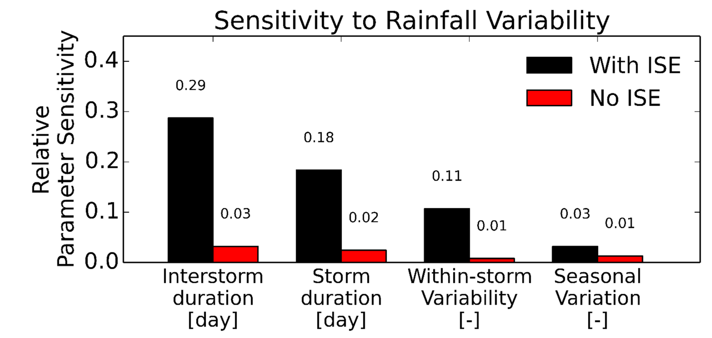
Result 2: Simulated TTDs are very sensitive to mean annual precipitation.

Figure 7. Intensity vs. age. There is a strong relationship between the annual fraction of young water < 2 months old (Fyw) in discharge and the annual mean rainfall intensity (panel “A”) and the standard deviation of annual rainfall (panel “B”), both with and without the inverse storage effect (ISE).



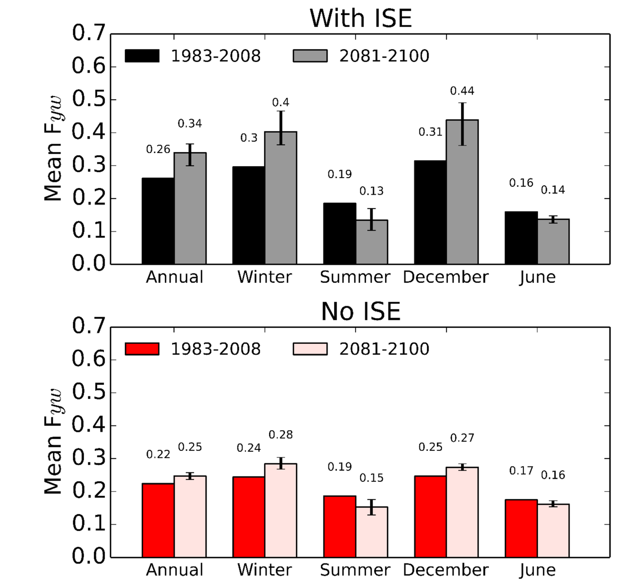
Result 3: The TTD is more sensitive to rainfall pattern when the ISE is included in the model.

Figure 8. Sensitivity to rainfall pattern. The Fyw in catchments with an ISE is sensitive to changes in the interstorm duration, storm duration, and within storm variability. The y-axis is the percent change in the mean annual Fyw per percent change in the parameter. Note changes were made one-at-a-time.



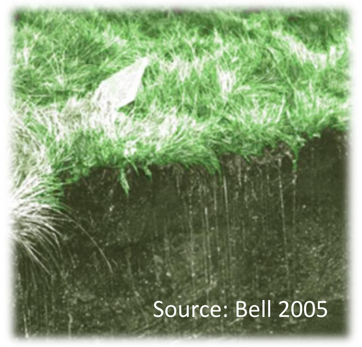
Result 4: The TTD is more sensitive to projected future rainfall scenarios when ISE is included in the model.

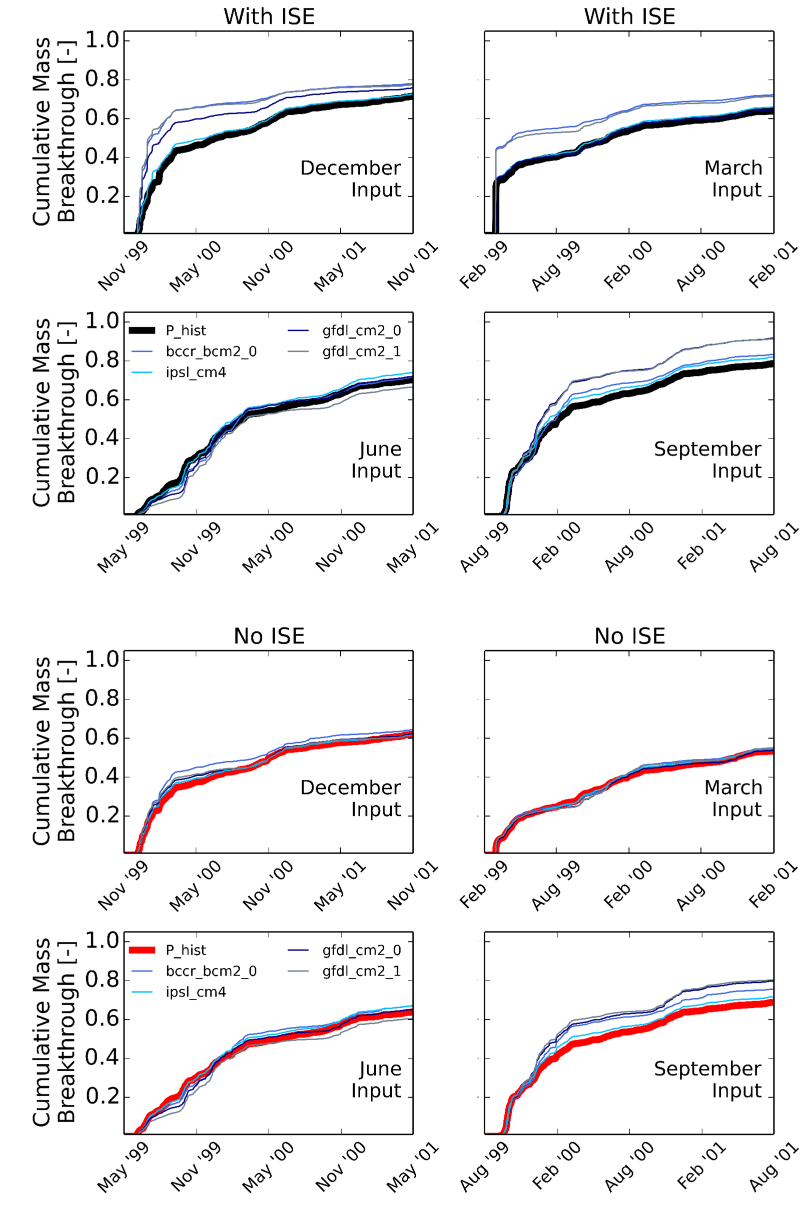
Figure 9. Sensitivity to rainfall changes. The top plot (the ISE scenario) shows larger changes in Fyw that the bottom plot (the no ISE scenario) under different downscaled rainfall scenarios for 2081-2100 (see figure 5), especially in winter. The error bars show the range of results from the four GCMs considered.



Result 5: Breakthrough curve simulations show that climate change could accelerate transport, especially in catchments with a strong ISE.

Figure 10. Breakthrough curves and climate change. The plots show the breakthrough curve for a unit mass of conservative tracer diluted in rainwater falling in December, March, June, or September 1999/2099 for catchments with ISE (top 4 panels) and no ISE (bottom 4 panels). The sensitivity of the breakthrough curve to rainfall changes is much higher for catchments showing an ISE, where there is immediate accelerated transport in December and March, and delayed accelerated transport in September. Figure 8 suggests that at least some of this difference can be attributed to the different influence of rainfall pattern on the two cases.





What did we learn?

- A coupled hydrologic / transport model was built and validated to simulate the relationship between rainfall variability, catchment storage effect, and time-varying TTDs.
- Simulation results based on Plynlimon base case data suggest that:
  - Simulated TTDs are very sensitive to mean rainfall intensity.
  - The TTD for catchments with an inverse storage effect (ISE) is more sensitive to rainfall pattern.
  - TTDs and breakthrough curves for catchments with an ISE is more sensitive to projected changes in rainfall variability under climate change.
- Model uncertainty may be relatively high in scenario runs that are substantially different from calibration conditions.
- Results suggest that the strength of the ISE in a particular watershed may be a useful indicator of the sensitivity of local transport to rainfall variability and climate change.

References

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