Evaluating travel time distributions of macroporous hillslope

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Introduction

- Travel times of soil water contain useful information about flowpaths in catchments. The travel time distribution is often used as a fundamental metrics of the catchment or hillslope hydrological response.

- When lumped convolution approaches are applied to determine the travel time distribution, a prior assumption about the type distribution needs to be made. Alternatively, travel time distributions can be evaluated by more advanced numerical models integrating the dynamics of subsurface water flow and solute transport.

- Physically–based models of flow and transport can be used to estimate soil water travel times in hillslope soils exhibiting significant lateral preferential flow effects.

Travel time distributions

The travel time distribution function is defined as the response of a catchment/hillslope to a unit tracer input represented by the Dirac delta function:

$$J_{\text{out}}(t) = M \underbrace{g(t)}_{\text{Aggregate travel time distribution}} = M_1 \underbrace{g_1(t)}_{\text{Travel time distribution of stormflow}} + M_2 \underbrace{g_2(t)}_{\text{Travel time distribution of deep percolation}} + M_3 \underbrace{g_3(t)}_{\text{Travel time distribution of transpiration}}$$

$$= \int_{\Omega_1} c(t,\mathbf{x}) q(t,\mathbf{x}) d\Omega + \int_{\Omega_2} c(t,\mathbf{x}) q(t,\mathbf{x}) d\Omega + \int_{\Omega_3} c(t,\mathbf{x}) S(t,\mathbf{x}) d\Omega$$

The partial travel time distributions for the relevant hillslope discharge processes (subsurface stormflow, deep percolation and transpiration) and the aggregate travel time distributions characterizing the combination of all discharge processes were evaluated.

Methods used in this study

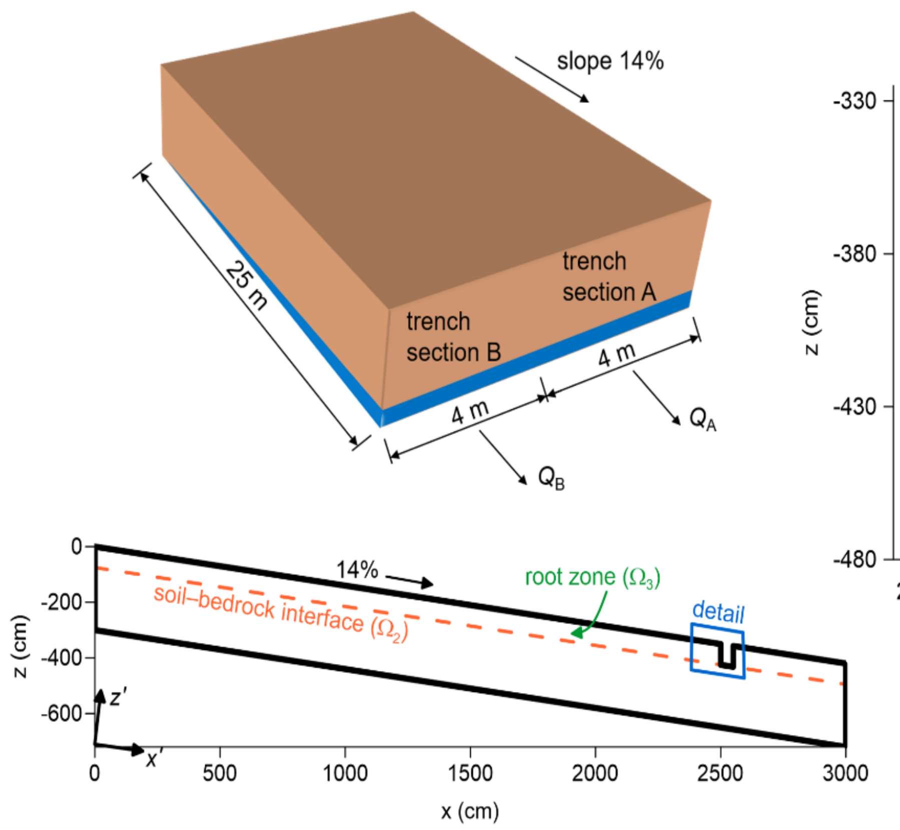
- A two-dimensional dual-continuum model, previously validated on water flow and oxygen-18 data (Dusek and Vogel, 2018 JH), was used to evaluate travel time distributions at a hillslope site.

- A fictitious conservative tracer, entering the hillslope surface in the form of a nearly instantaneous pulse at the beginning of the simulated period, was applied.

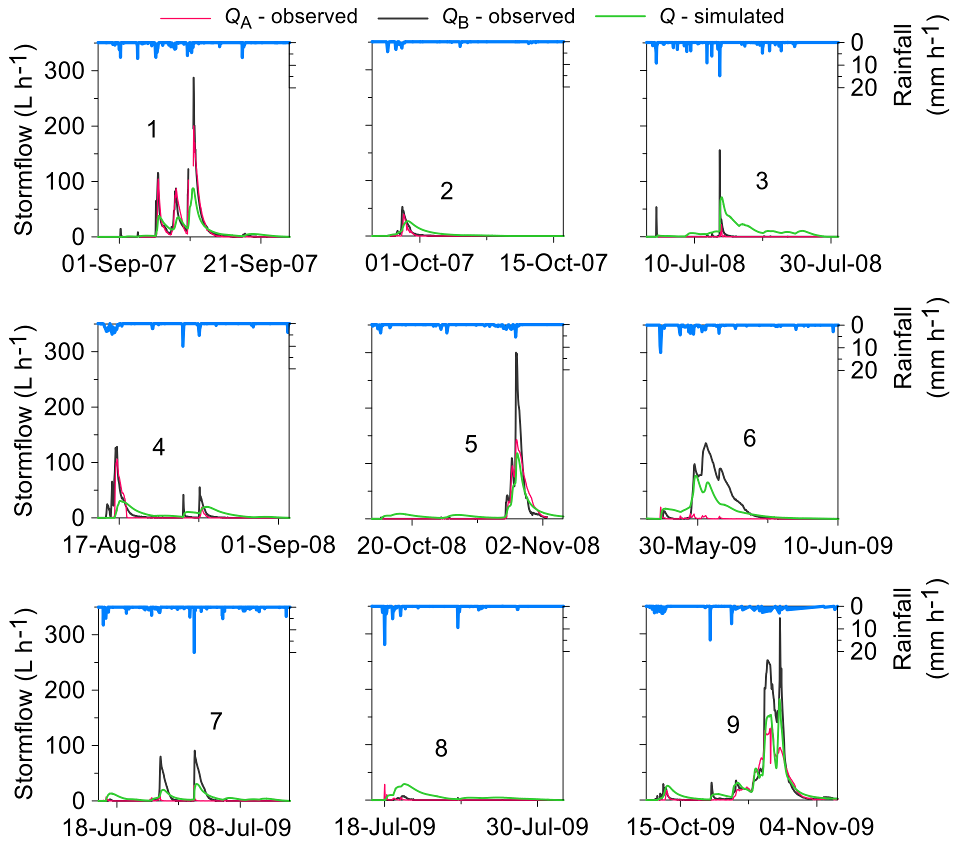
- The breakthroughs of the tracer were analyzed and the associated travel time distributions were estimated at both **episodal** and **seasonal** time scales.

- The numerical experiments were performed for three growing seasons (2007, 2008, and 2009) and nine major rainfall–runoff episodes.

Two-dimensional flow and transport model

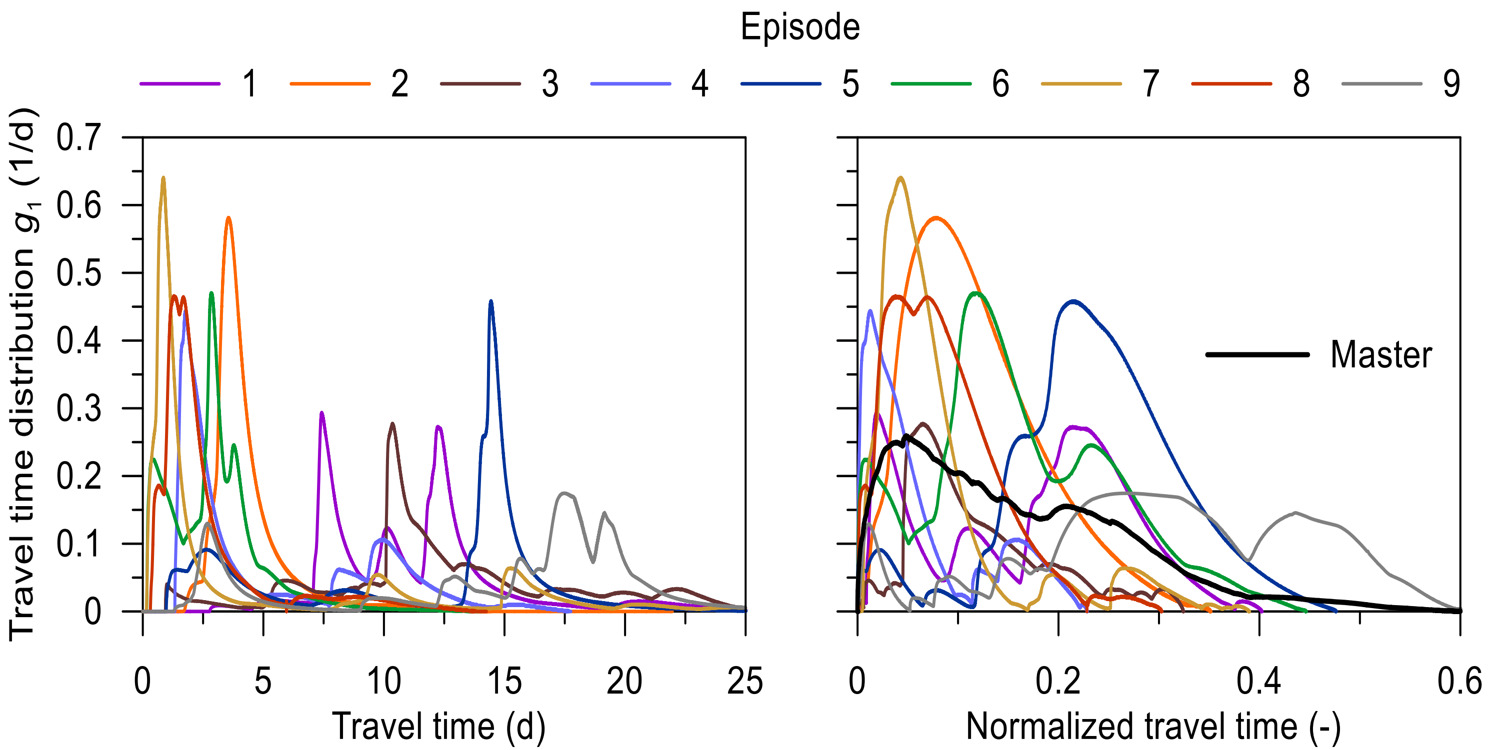


Schematics of the experimental hillslope with subsurface trench (observed stormflow Q_A and Q_B) and 2D flow domain with boundaries Ω_1, Ω_2 and Ω_3.



Nine selected major rainfall–runoff episodes during growing seasons 2007, 2008, and 2009.

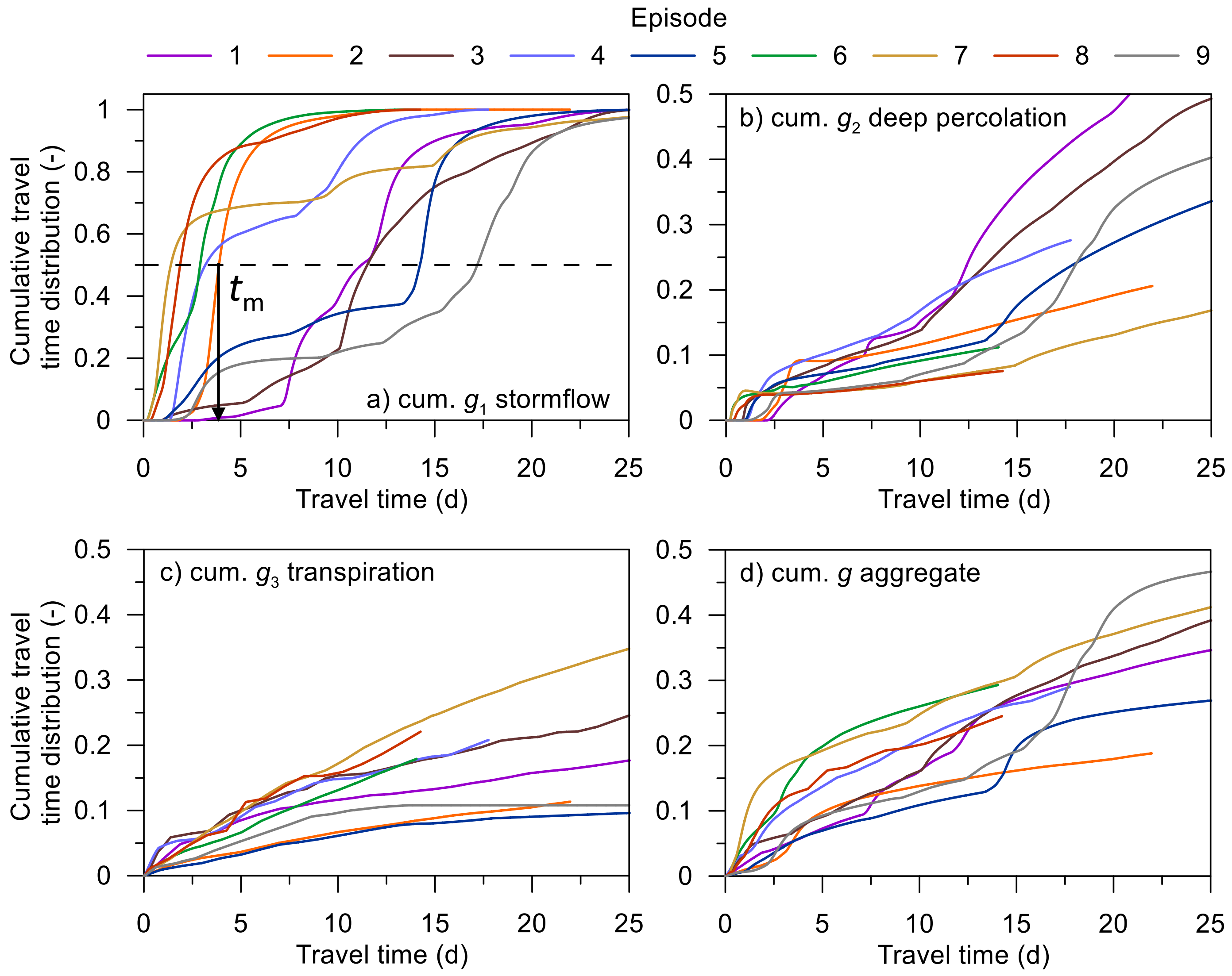
Episodal travel time distributions for stormflow



Evaluation of master travel time distribution for stormflow based on nine episodes.

Flow-corrected travel time obtained as the cumulative volume of stormflow divided by the final volume of rainfall.

Episodal cumulative travel time distributions

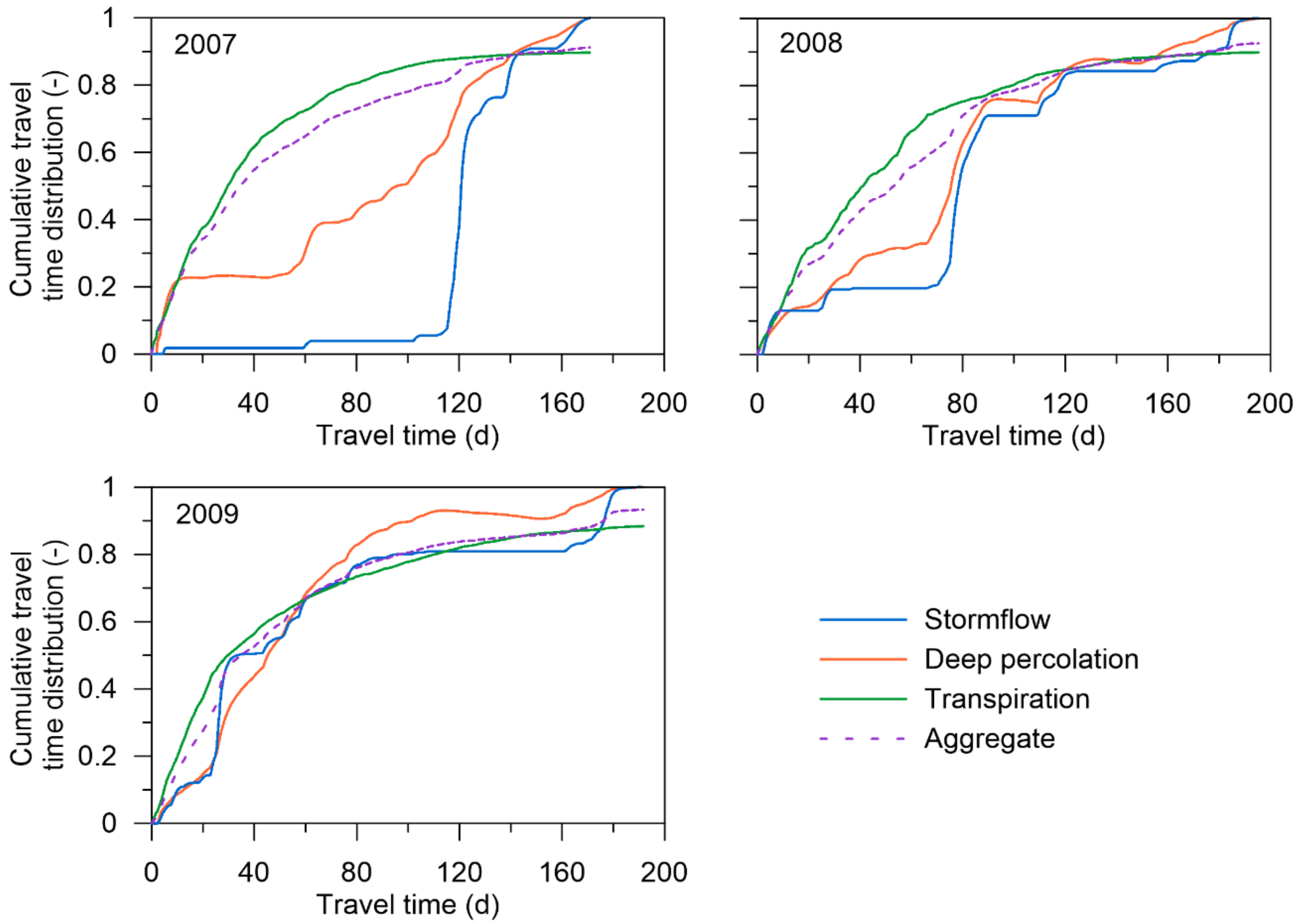


Estimated median travel times t_m of stormflow

Episode	1	2	3	4	5	6	7	8	9
t_m (days)	11.2	3.9	11.5	3.2	14.2	2.9	1.4	1.9	17.2

The estimated median travel times of stormflow vary significantly among the rainfall–runoff episodes.

Seasonal travel time distributions



Estimated median travel times (in days)

Season	2007	2008	2009
Stormflow	120.9	78.5	33.5
Deep percolation	95.8	75.5	35.4
Transpiration	26.4	35.4	23.5
Aggregate	30.4	46.2	30.1

Significantly different seasonal median travel times were found for different discharge processes. The shortest median travel times were determined for transpiration. As expected, the stormflow t_m values showed the greatest interseasonal variability compared to the other two discharge processes.

Summary and conclusions

- The episodal travel time distributions suggest a quick hydrological response of the hillslope to rainfall, which can be attributed to the inclusion of preferential flow component in the model.
- The variability of the travel time distributions was found to be controlled by the meteorological conditions during the rainfall–runoff episodes and the soil moisture distribution prior to the episodes.
- The episodal median travel times of subsurface stormflow ranged from 1 to 17 days for the selected rainfall–runoff episodes.
- The seasonal aggregate median travel time (for all discharge processes combined) was estimated in the range of 30–46 days.
- Transpiration was shown to have significant impact on the estimated seasonal as well as episodal aggregate travel time distributions.

More information:
Modeling Travel Time Distributions of Preferential Subsurface Runoff, Deep Percolation and Transpiration at A Montane Forest Hillslope Site, Water, 2019, doi:10.3390/w11112396.