

# Can a simple lumped parameter model simulate complex transit time distributions?

## Benchmarking experiments in a virtual watershed.

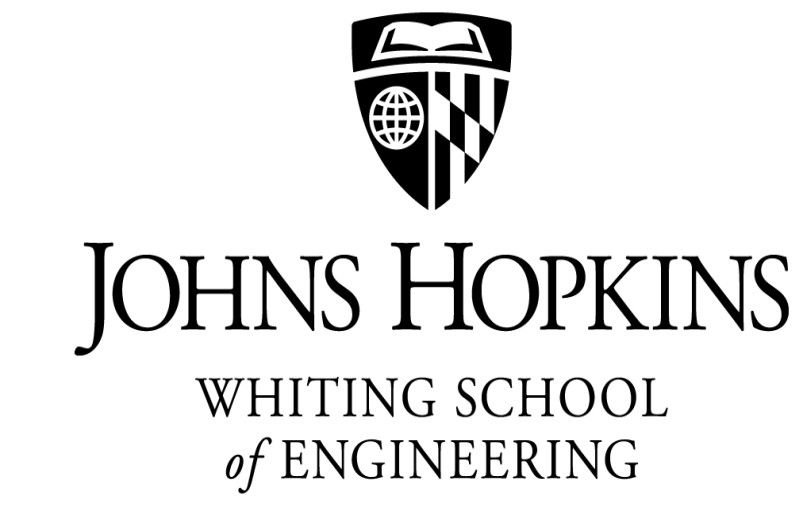
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### 1. Abstract

#### Motivation

- The catchment transit time distribution (TTD) is the time-varying, probabilistic distribution of water travel times through a watershed.
- The TTD is a useful descriptor of catchment flow and transport processes, but is temporally complex and cannot be directly observed at watershed scale.
- Traditional “steady-state” TTD models assume that the time-variability of the TTD can be neglected [2].
- Recent advances in both distributed [e.g., 7] and lumped parameter [e.g., 15] TTD models relax the steady-state assumption.
- The goal of this research is to use recent advances in TTD modeling to improve our understanding of what controls time-variable transport through landscapes, and how to model it at catchment scale.

#### Experimental objectives

- To simulate the time-varying TTD in a “benchmark” virtual watershed using state-of-art distributed modeling and field data.
- To compare simulations of the “virtually-true” TTD with (a) time-invariant and (b) time-varying lumped parameter models.
- To analyze how the time-variability of the simulated TTD is related to virtual watershed characteristics and climatic conditions.

#### Methodological notes

- The hydrology of a virtual watershed was simulated using PARFLOW with field intelligence from a small USDA experimental catchment in PA, USA.
- SLIM-FAST particle tracking was used to estimate the TTD in four constant rainfall scenarios, representing periods of low to high rainfall. Future work will consider time-varying rainfall and ET.
- Work is ongoing to improve the ability of the PARFLOW model to match observed hydrology.

#### What we found (preliminary)

- Median transit times doubled from 1 to 2 years in high to low rainfall.
- The TTD of rainfall onto the riparian zone was relatively constant across scenarios. The TTD over hillslopes was much more variable.
- This localized sensitivity to rainfall was associated with the topographic wetness index and shifts in groundwater level.
- The sensitivity of the catchment TTD to rainfall scenario can be parsimoniously described using rank StorAge Selection (rSAS) functions.



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### 1. Benchmark hydrologic model: PARFLOW

A virtual modeling testbed was constructed using the fully distributed PARFLOW (PARAllel FLOW) model [3-6] with SLIM-FAST particle tracking code [7].

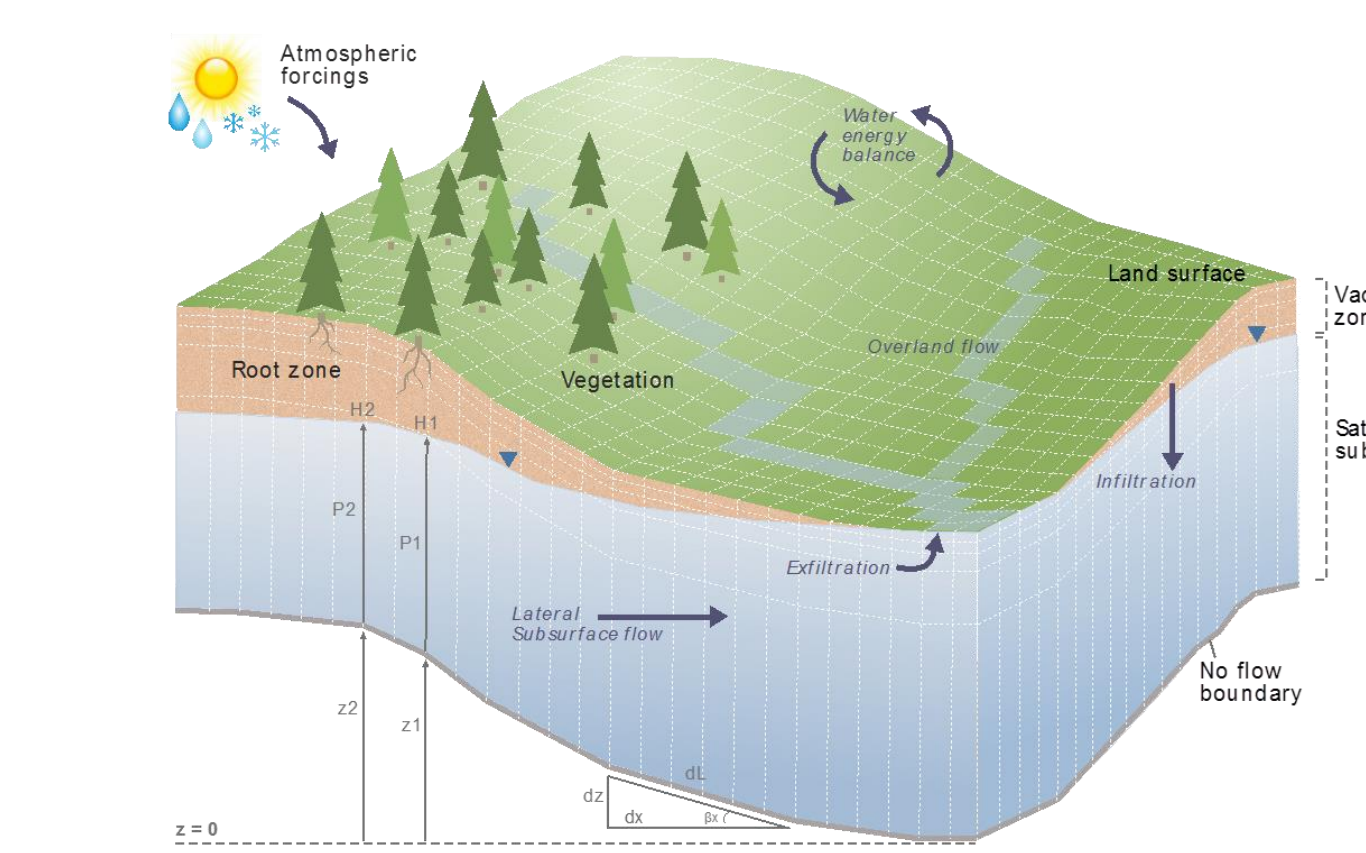


Figure 1. Schematic of the PARFLOW model. Image from [1].

Subsurface flow (Richard's equation):

$$S_s S(\psi) \left( \frac{\delta \psi}{\delta t} \right) + \phi \frac{\delta S(\psi)}{\delta t} = \nabla \cdot [k(x) k_r(\psi) \nabla(\psi - z)] + q_s$$

Overland flow (kinematic wave and Manning's equation):

$$\frac{\delta \psi_s}{\delta t} = \nabla \cdot (v \psi_s) + q_r(x)$$
$$v_x = - \left( \frac{\sqrt{S_{fx}}}{n} \right) \psi_s^{\frac{2}{3}} \text{ (same for } v_y \text{)}$$

Particle tracking:

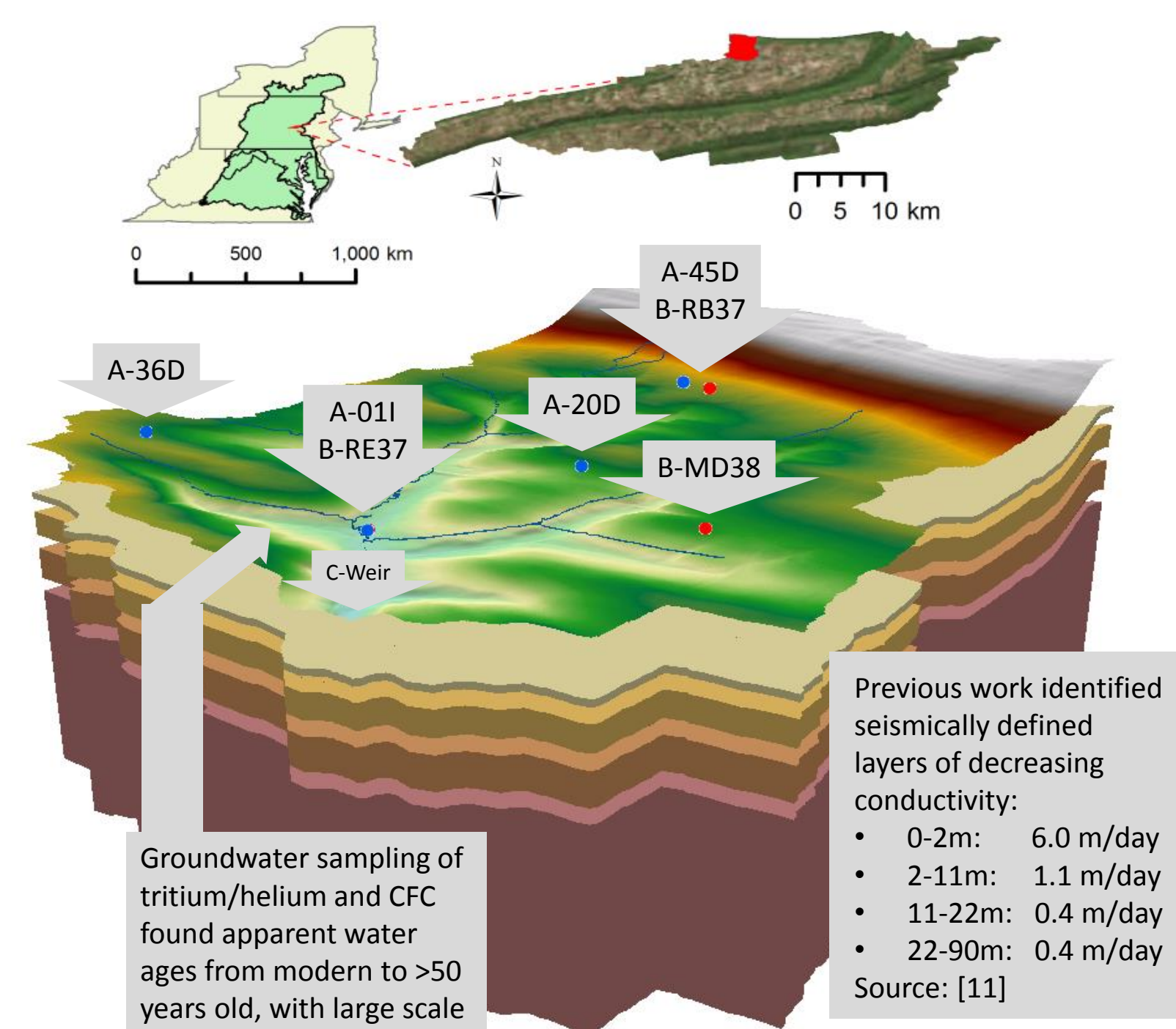
$$\frac{dx}{dt} = v$$

### 2. Model testbed site: WE-38

WE-38 is a 7.3 km<sup>2</sup> sub-watershed within the USDA's Mahantango experimental catchment.

The PARFLOW model was parameterized with field data from WE-38 describing topography (120m res.), and permeability and porosity (3 uniform layers of increasing thickness).

Figure 2. Map of the WE-38 catchment in PA, USA.



### 3. Constant rainfall scenarios: low to high

Forward particle tracking was used to simulate the steady-state TTD under four rainfall scenarios. The scenarios represent 50-200% of the long-term average effective precipitation.

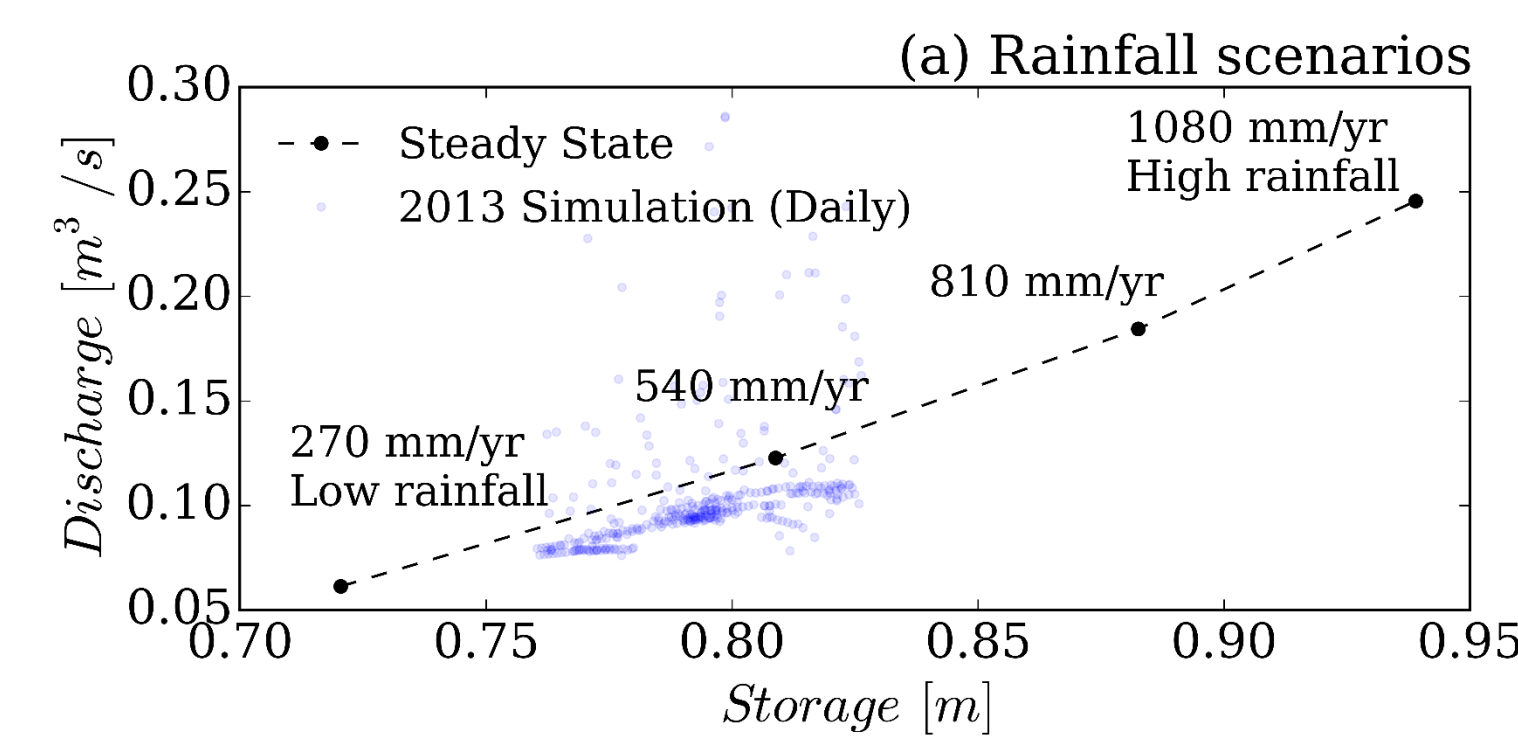


Figure 3. Each black point indicates the steady-state storage and discharge for each of the four rainfall scenarios. The blue points mark S and Q for each day of a 1-year simulation using observed effective rainfall (see box 4).



### 4. Preliminary model development and evaluation

PARFLOW was used to simulate hourly 2013 hydrology. There are significant differences between observed and simulated results. Model development is ongoing.

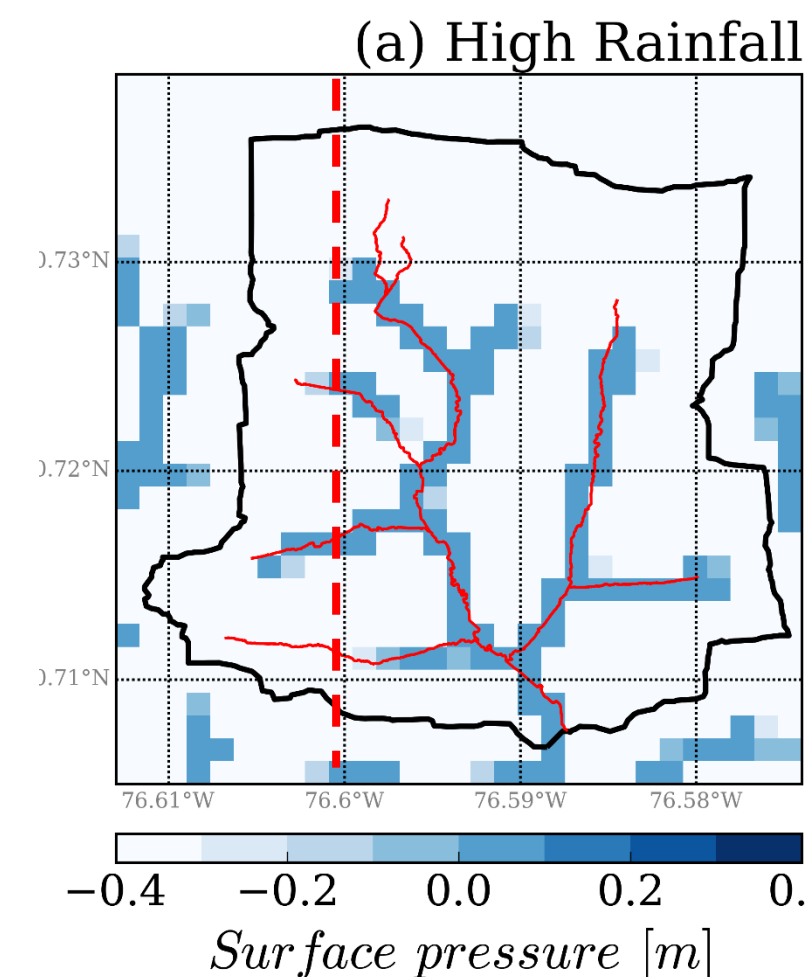
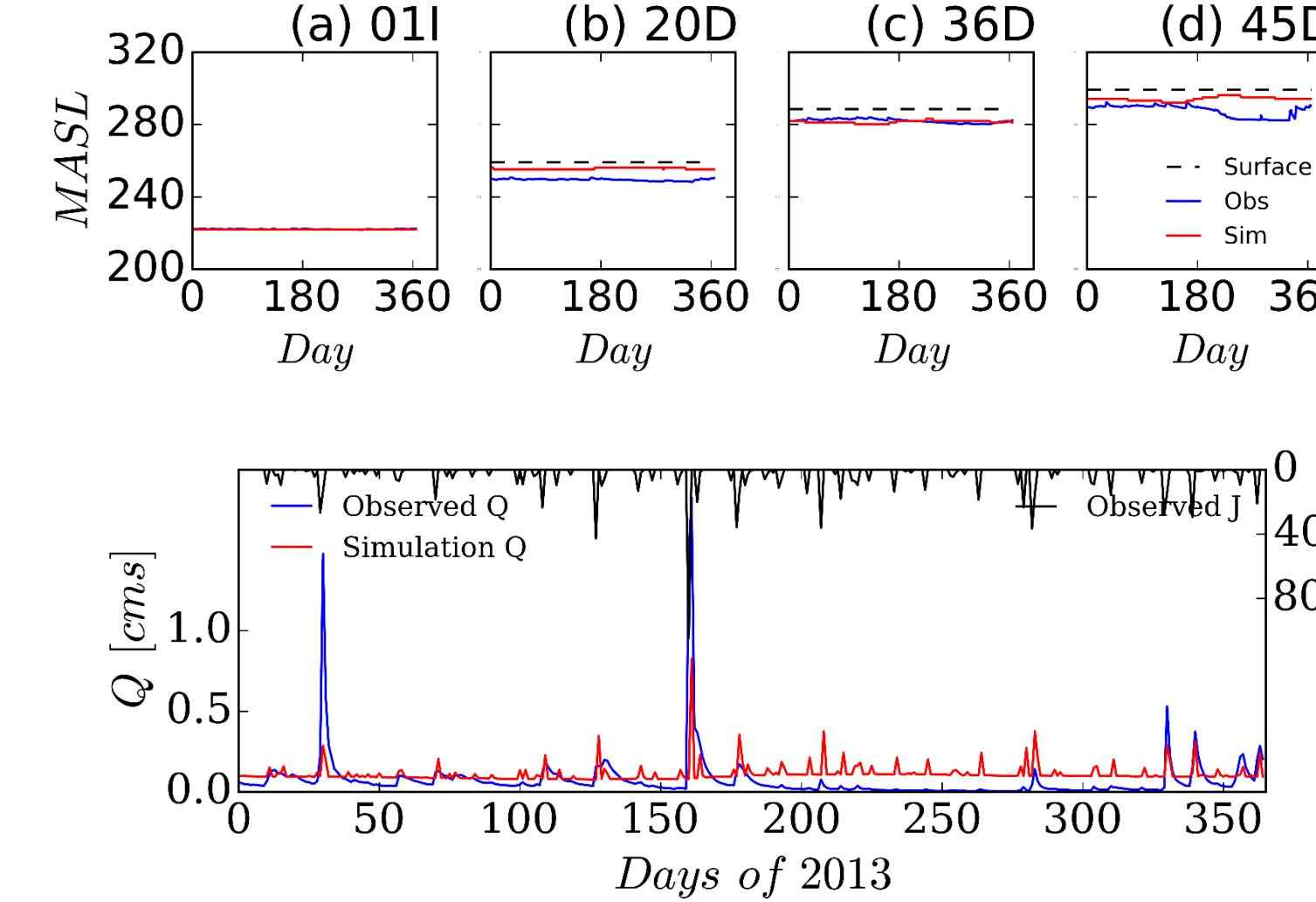


Figure 4. The upper panels compare observed and simulated water level in four wells (see Fig 2) and discharge over 2013. The comparison shows important differences and similarities. The left panel shows the general pattern of surface pressure observed in the high rainfall scenario, which was similar in all scenarios. Ponding occurs over the stream channel, as expected.

### 5. Transit times under low and high rainfall

Travel times are significantly higher in the low rainfall scenario compared to the high rainfall scenario.

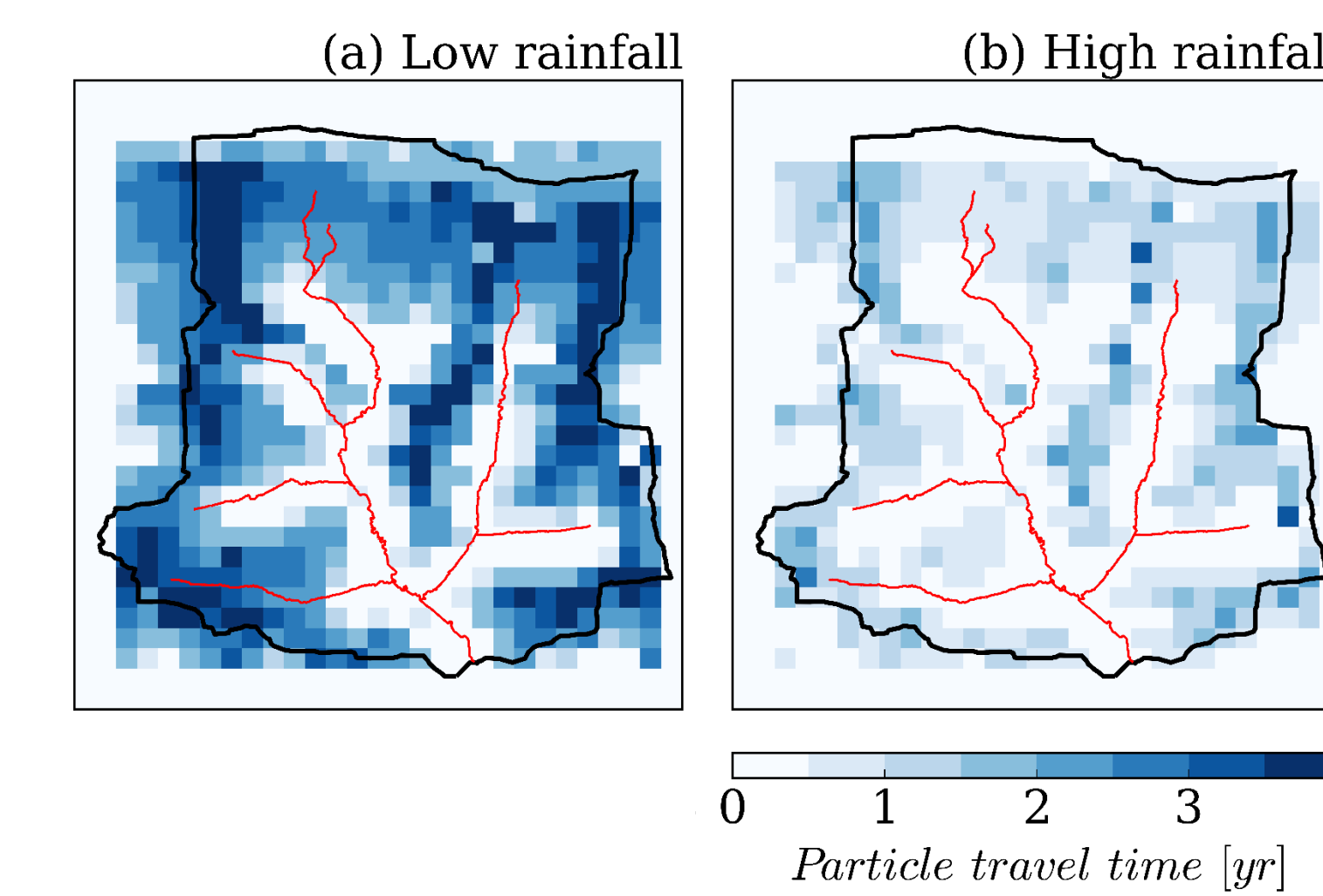


Figure 5. The interpolated transit time of 6000 particles applied to the surface for the low and high rainfall scenarios.

### 6. Spatial dependence of TTD variability

High rainfall causes a larger decrease in particle transit times in the hillslope area compared to the riparian area.

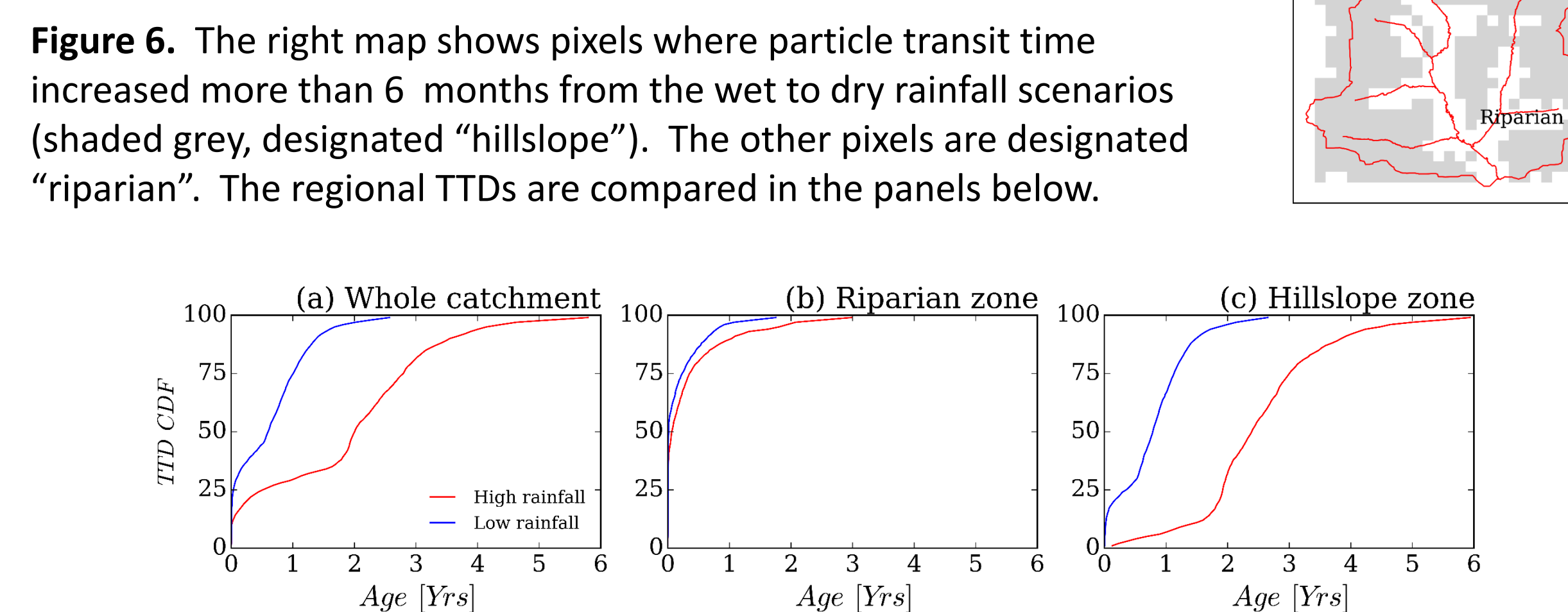


Figure 6. The right map shows pixels where particle transit time increased more than 6 months from the wet to dry rainfall scenarios (shaded grey, designated “hillslope”). The other pixels are designated “riparian”. The regional TTDs are compared in the panels below.

### 7. Transit times and the topographic index

Preliminary analysis suggests that the TTD of rainfall over regions with high topographic wetness index [16] is less sensitive to changes in rainfall.

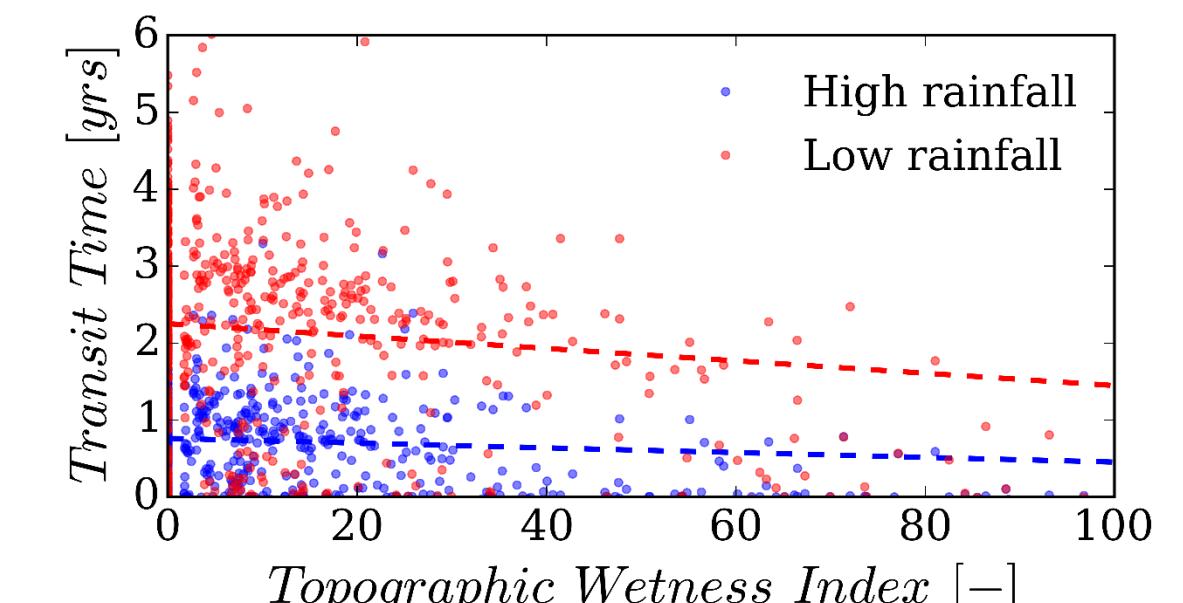


Figure 7. Pixel by pixel comparison of topographic wetness index versus particle transit time across the WE-38 watershed. Dotted line indicates line of best fit, which have negative slopes (p<.01).

### 8. Transit times and subsurface saturation

Qualitative analysis of the subsurface saturation and groundwater table shows more variability in the hillslope region. This implies that the observed shifts in transit times may be related to vadose zone processes, as suggested by [12].

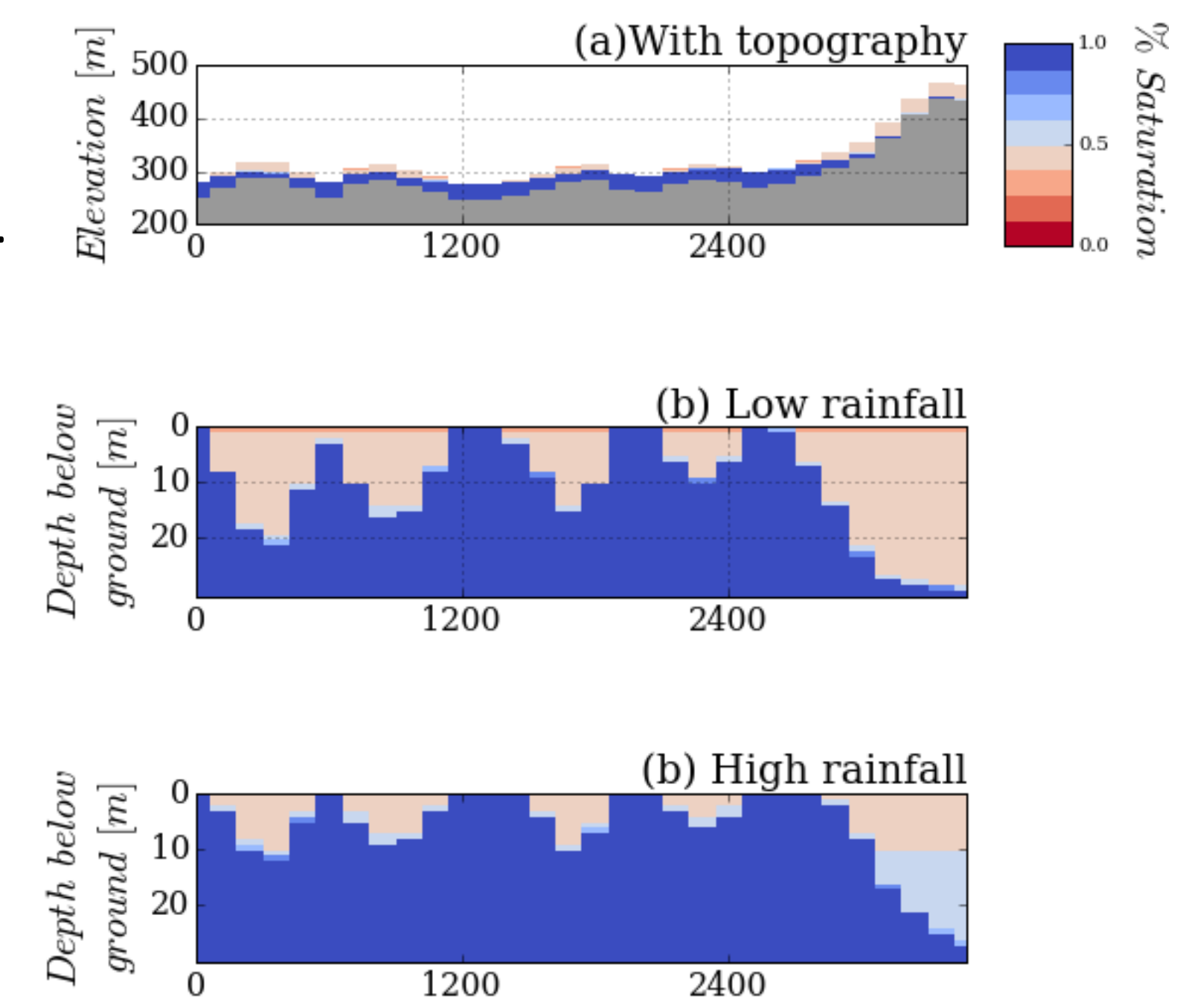


Figure 8. Subsurface saturation across the red-dotted N-S transect shown in Fig 4. The topography in the top panel gives context for interpreting the lower panels. Note the higher saturation and water table in (C).

### 9. rSAS curves and a way forward

We use rank Storage Selection (rSAS) functions to describe the relationship between the distribution of water in catchment storage and the distribution of water ages in discharge for the four scenarios (see theory developed in [13-15]). Future work will look at whether these curves can be parameterized to generate a set of rSAS curves for any storage condition which, in turn, can be used to simulate time-variable TTDs with any hydrologic fluxes.

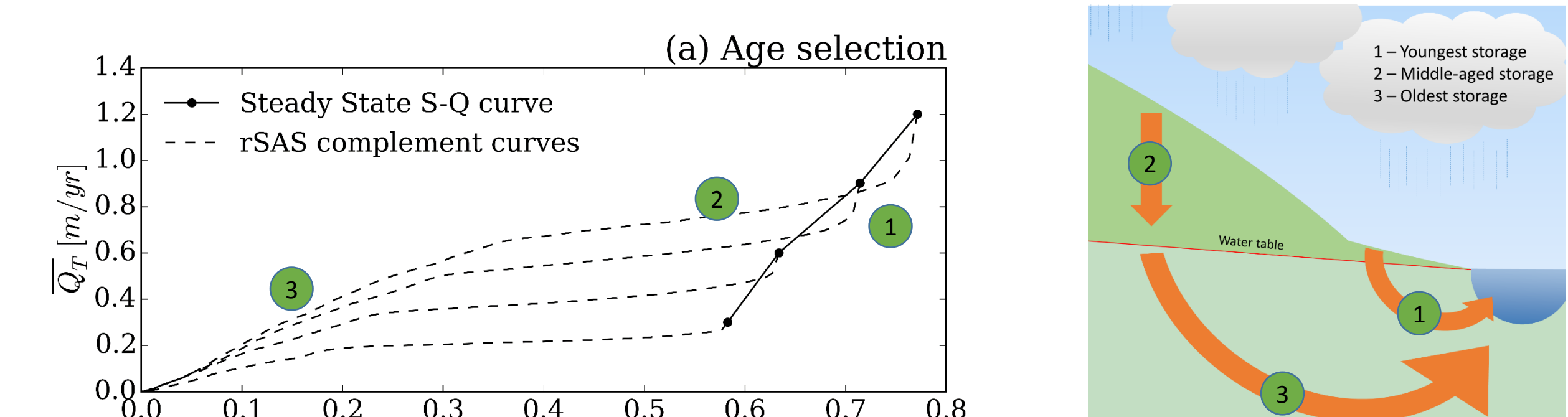


Figure 9. The left panel shows the set of rSAS curves calculated from the TTD of each rainfall scenario. The black dots show the active storage / discharge relationship. For each scenario, the dashed curve represents how much progressively older portions of storage (the x-axis) contribute to progressively older portions of discharge (the y-axis). The left panel shows a hypothesized conceptual model to explain the shape of the rSAS curves. The steep right-most drop in the high rainfall scenario shows that a large portion of discharge is coming from young storage, perhaps from near-river pathways. The middle plateau shows that relatively little middle-age-ranked storage reaches the outlet, which could be water traveling through the vadose zone. The linear drop in the rSAS function to the left is characteristic of uniform selection [15] and could be water that flowed through the vadose and saturated zone into the stream channel.