Evaluating travel time distributions of macroporous hillslope

Jaromir Dusek and Tomas Vogel

Czech Technical University in Prague, Faculty of Civil Engineering, Prague, Czech Republic

This study was supported by the Czech Science Foundation, projects no. 17-00630J and 20-00788S.
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:

\[ J_{\text{out}}(t) = Mg(t) = M_1 g_1(t) + M_2 g_2(t) + M_3 g_3(t) \]

\[ = \int c(t, x) q(t, x) d\Omega_1 + \int c(t, x) q(t, x) d\Omega_2 + \int c(t, x) S(t, x) d\Omega_3 \]

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.

Schematics of the experimental hillslope with subsurface trench (observed stormflow $Q_A$ and $Q_B$) and 2D flow domain with boundaries $\Omega_1$, $\Omega_2$, and $\Omega_3$. 
Episodical 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.
The estimated median travel times $t_m$ of stormflow vary significantly among the rainfall–runoff episodes.

<table>
<thead>
<tr>
<th>Episode</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_m$ (days)</td>
<td>11.2</td>
<td>3.9</td>
<td>11.5</td>
<td>3.2</td>
<td>14.2</td>
<td>2.9</td>
<td>1.4</td>
<td>1.9</td>
<td>17.2</td>
</tr>
</tbody>
</table>

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