Flow recession behavior of dendritic subsurface flow patterns

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Model concept

- Theory: subsurface flow patterns are organized after principles of optimality
- Assuming a power-law (quadratic) relation between hydraulic conductivity *K* and porosity *Φ*

$$\mathrm{K} = \mathrm{a}\Phi^{n} \; with \; n = 2$$

- Power-law dependencies of porosity and conductivity on the flux density (Darcy velocity) *q*

$$\Phi \propto q^{\frac{2}{n+1}} \qquad \mathrm{K} \propto q^{\frac{2n}{n+1}}$$

- Preferential flow paths towards the grid boundaries (1024×1024 nodes) are optimized towards minimum energy dissipation
- Fixed distribution of hydraulic conductivity *K* and porosity *Φ*
- Catchment size is measured in pixels, catchments consisting of a single pixel have $\Phi = 1 \; and \; K = 1$
- Grid spacing is used as length scale

Optimal Channel Networks (OCNs)

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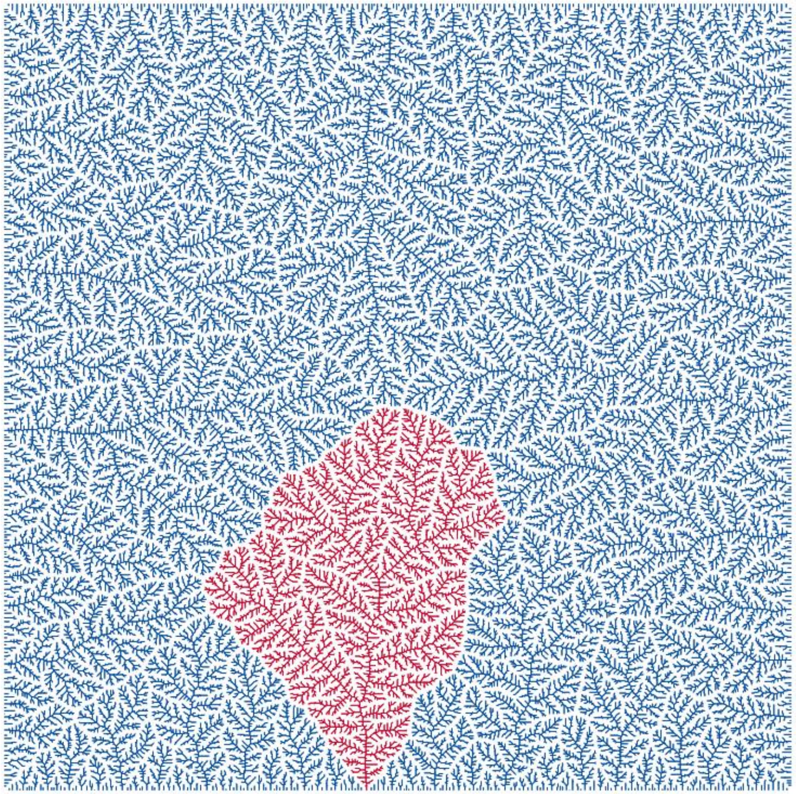

Figure 1: Preferential flow paths used in the model. The biggest individual catchment (110323 pixel) is highlighted in red.

- Each node has a unique flow direction towards one of its neighbours but can have multiple donating nodes
- Resulting optimal channel networks have a tree-like structure and form dendritic flow patterns

Flow equation

- Linear storage behavior
- Time-dependent mass balance for node *i* with storage coefficient $S_i = \Phi_i$ (proportional to porosity), hydraulic head *h*, donating nodes *j*, and recharge *r* :

$$S_i \frac{d}{dt} h_i = \sum_j q_j - q_i + r_i$$

- Flux density/Darcy velocity *q* for node *i* with flow target *b* and distance between both nodes *d* :

$$q_i = K_i \frac{h_i - h_b}{d_i}$$

- Implicit time discretization of the diffusion equation

$$S_i \frac{h_i(t+\delta t) - h_i(t)}{\delta t} = -q_i(t+\delta t) + \sum_j q_j(t+\delta t) + r_i(t+\delta t)$$

Recession analysis

- Steady state scenario: constant recharge rate $r_i(t) = 1$ for $t < 0$ until steady state conditions are met
- Recharge drops to zero at $t = 0$
- Fluxes and hydraulic heads for all nodes are calculated recursively in upstream direction for each time step (see supplementary material)
- Discharge for each catchment is measured at the outlet node at the boundary of the grid

Recession behavior

- Recession behavior is similar for all catchments
- Baseflow component: Exponential decay at large time scales (indicated by a straight line in a semi-logarithmic plot)
- Small deviation from exponential function at early stages of recession

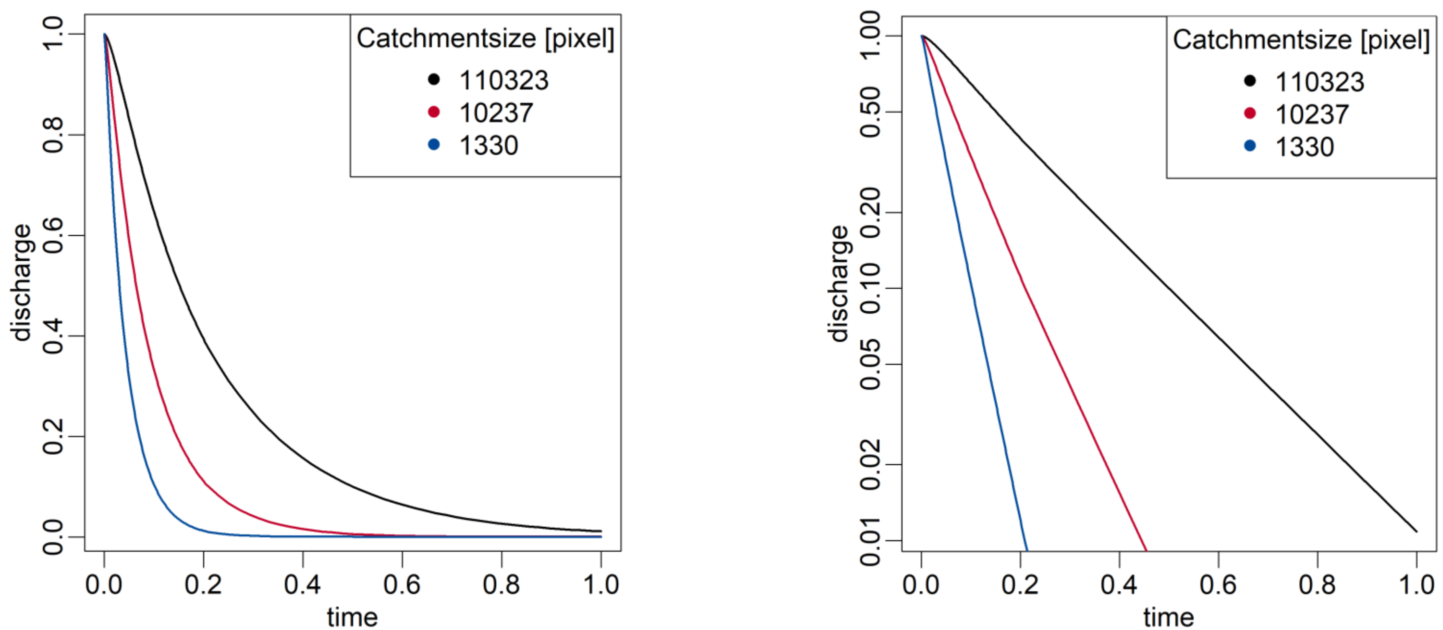

Figure 2: Recession curves for three different catchment sizes in a linear (left) and semi-logarithmic plot (right).

Baseflow share

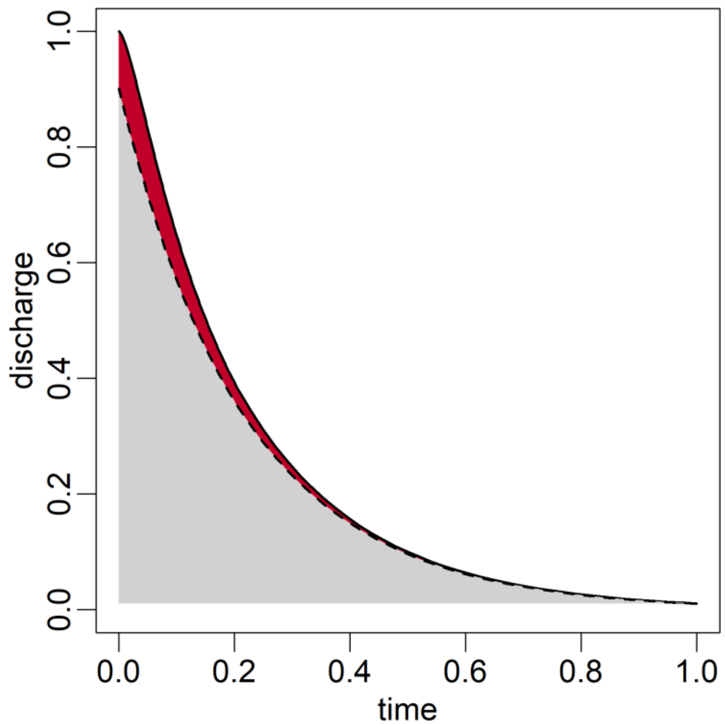

Figure 3: Recession curve of an individual catchment (solid line) and the projected exponential baseflow (dashed line). The gray area corresponds to the amount of water that is drained as baseflow, whereas the red area corresponds to the amount not part of the baseflow.

- Baseflow component of the modelled aquifer is assumed to follow an exponential function throughout the entire recession period
- > 85 % of the total amount of water is drained as part of this baseflow component (baseflow share)
- Baseflow share is not closely related to the catchment area

Recession coefficient

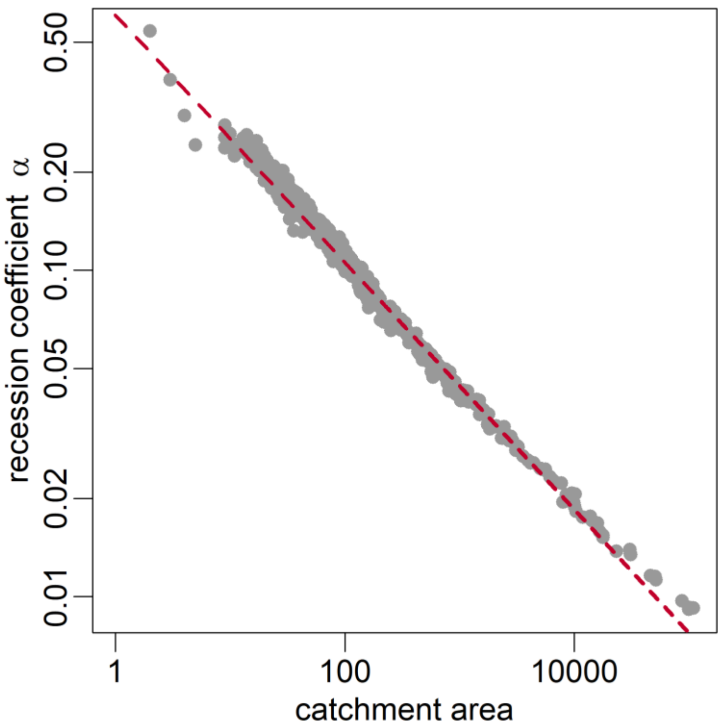

Figure 4: Recession coefficients of all catchments plotted against catchment area double-logarithmically.

- The recession coefficient α of the exponential function is proportional to the catchment area $\alpha \propto Area^{-1/3}$
- Relation is weaker than for simple 1D ($\propto Length^{-2}$) or 2D ($\propto Area^{-1}$) block models

Summary & Outlook

- Dendritic patterns of preferential flow paths produce recession curves with exponential behavior at large time scales (baseflow)
- The exponential component accounts for over 85 % of the total amount of drained water during the recession period
- The recession coefficient is proportional to the area of the respective catchment

Next steps:

- Sloped aquifers: Add topography to the network
- 3D model: Flow in horizontal and vertical direction

Supplementary material

- Hydhead_completegrid.mp4

  Hydraulic head values (nondimensional) for the complete model grid (1024×1024 nodes) over time. High values are coloured in brown, low values in green. Watershed of one individual catchment (size of 110323 pixel) is drawn in black (cf. Figure 1). The inset in the top-right corner shows the recession curve of the highlighted catchment.