A physically-based numerical model of catchment water flow to evaluate dominant controls of residence time distributions

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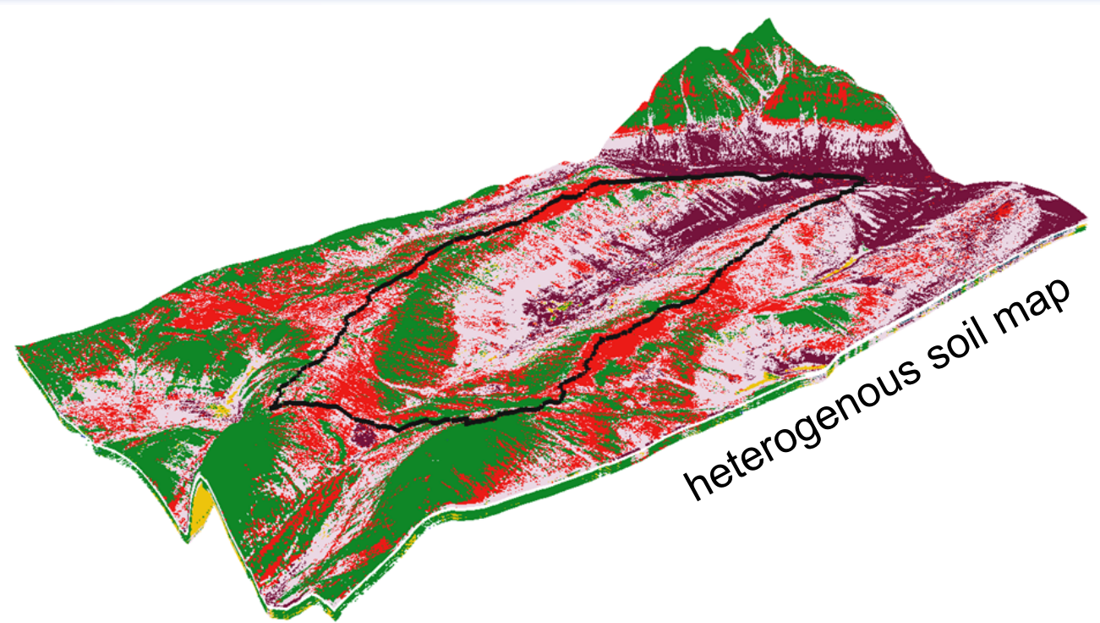
1 Introduction

The residence time distribution (RTD) of water in catchments is a promising tool to characterize and model solute transport on a larger scale. Since RTD's cannot be measured directly, numerical water flow models and particle tracking algorithms are valuable tools. A coupled surface and subsurface flow model was created for a small catchment within the Harz Mountains, Germany. Here we present a new approach to obtain RTD directly from velocity fields which were generated with our numerical model. Our objectives are to systematically evaluate the impact of varying geometries and groundwater recharge rates on RTD's for steady state simulations. Additionally, transient simulations were performed to investigate dynamic RTD and reveal the dominant controls of catchment characteristics.

2 Modelling approach

- HydroGeoSphere (HGS - Aquanty Inc.)



Model properties:

Area = ~ 1.600.000 m²
Complexity = ~ 20.000 nodes / 1 to 50 m resolution
Layer = 2 to 12 unique independent layers
Min. depth = varying domain bottom 2 to 50m
Boundaries = precipitation (surface & root zone), pot. evapotranspiration (surface & root zone), critical depth (outlet), varying domain bottom (bedrock) as no flow

Model input:

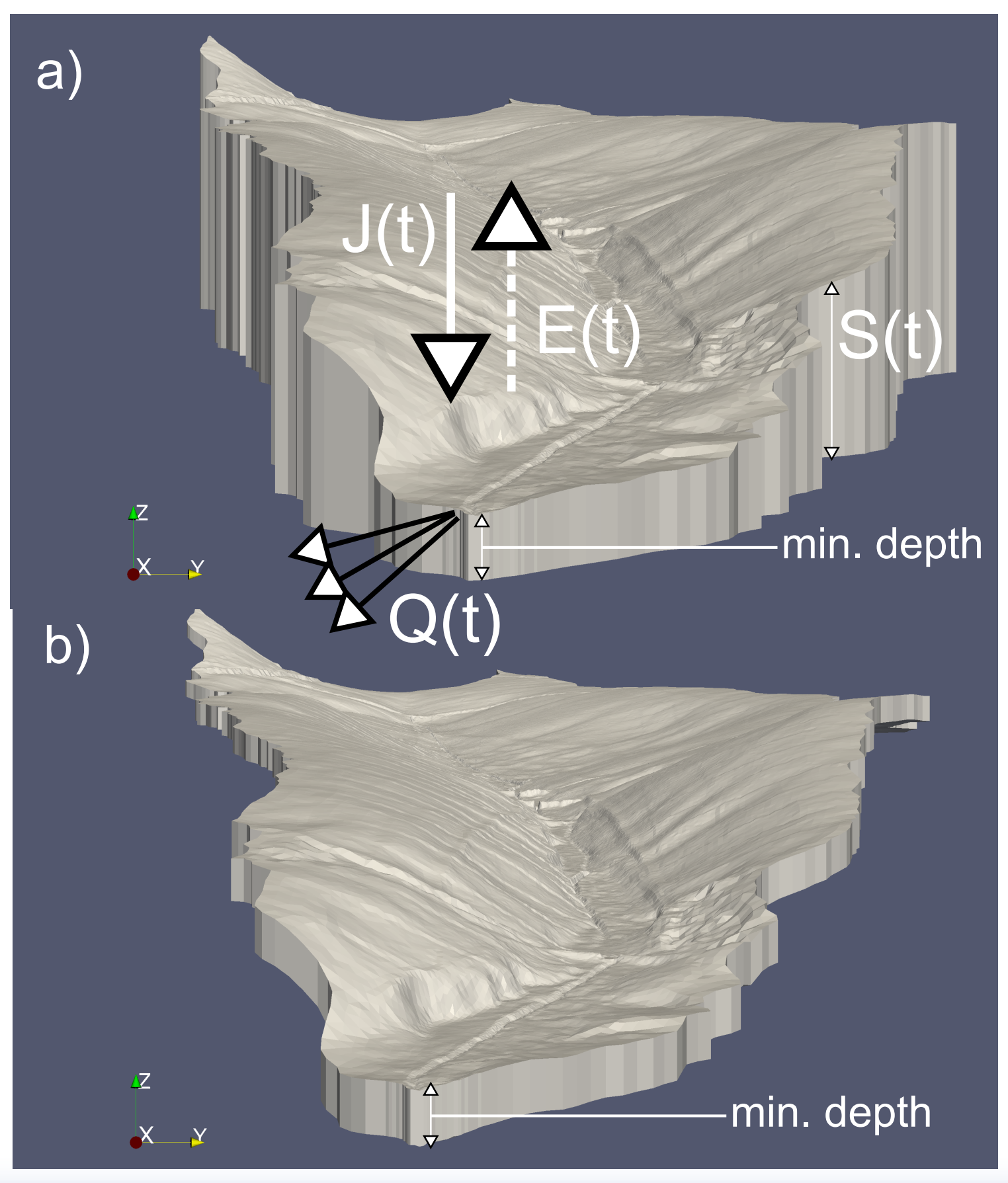
precipitation = transient time series (70's - today)[1]
evapotranspiration = transient time series (90's - today)[1], calculated with Penman-Montheith
soil properties = homogenous estimates or heterogenous (horizontal and vertical) interpolated properties with a vertically coupled random forrest approach

Model output:

heads, saturation- & flow velocity fields (porous media and overland flow), discharge, water balance, actual evapotranspiration

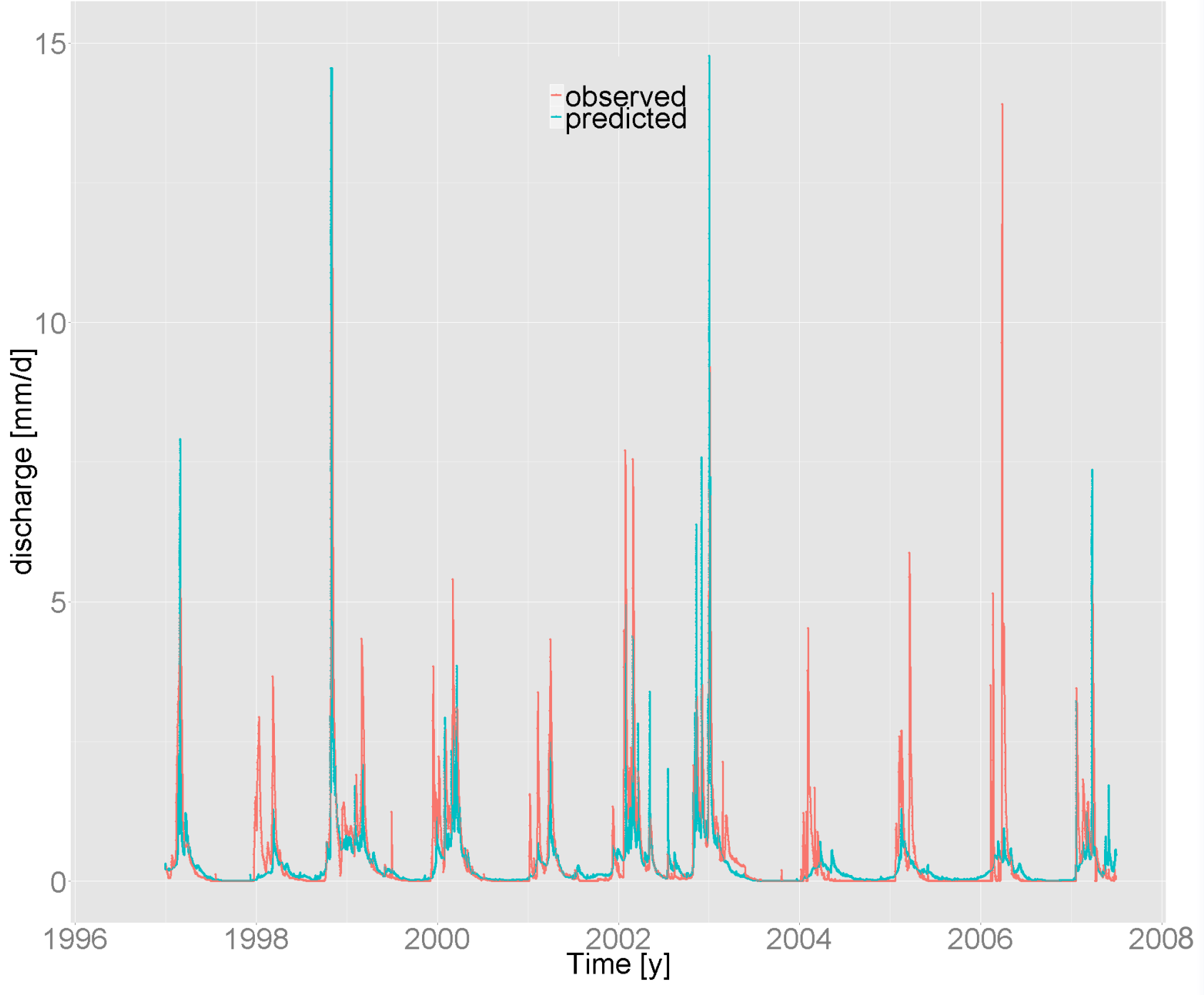
Steady state simulations

- fixed two-layered setup with homogenous soil properties (Van Genuchten, kf and porosity)
- variations of lower boundary depths (n = 5) and groundwater recharge rates (n = 15)
- two main domain bottom geometries (horizontal [a] and variable [b])



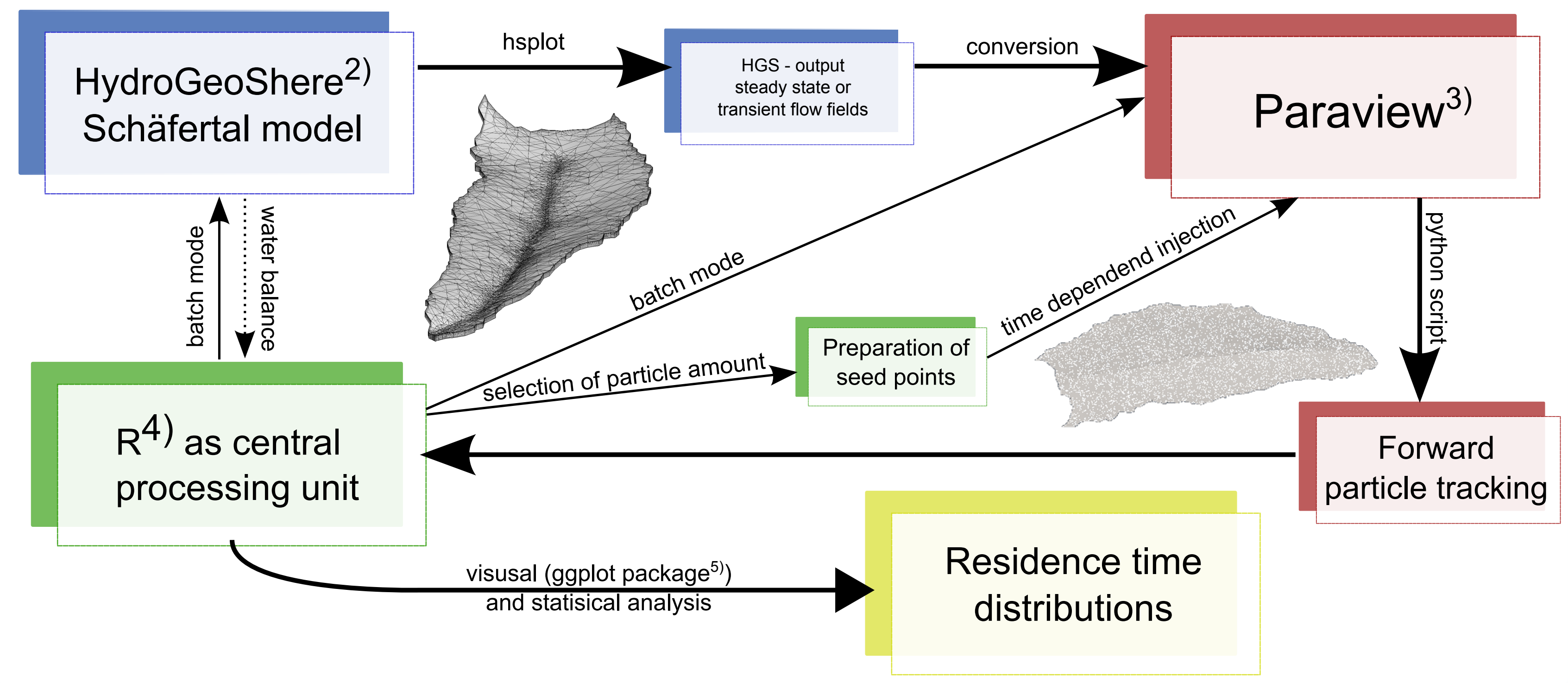
Transient simulations

- spatially distributed heterogenous soil properties
- transient meterological observations (10 year time series)
- no change in bottom geometries under transient conditions



- evaluated for water balance and NSE
- Nash–Sutcliffe model efficiency coefficient ~ 0.5
- PEST calibration currently under construction

3 Particle tracking and residence time derivation



HydroGeoShere[2] Schäfertal model

hsplot

HGS - output steady state or transient flow fields

conversion

Paraview[3]

python script

Forward particle tracking

batch mode

water balance

R[4] as central processing unit

batch mode

selection of particle amount

Preparation of seed points

time dependend injection

visusal (ggplot package[5]) and statisical analysis

Residence time distributions

References

[1] Time series provided by: University of Applied Sciences Magdeburg-Stendal, Department of Water and Waste Management, Magdeburg, Germany

[2] Brunner, Philip, and Craig T. Simmons. "HydroGeoSphere: a fully integrated, physically based hydrological model." Ground water 50.2 (2012): 170-176.

[3] Ahrens, James, Berk Geveci, and Charles Law. "Paraview: An end-user tool for large data visualization." The Visualization Handbook 717 (2005): 731.

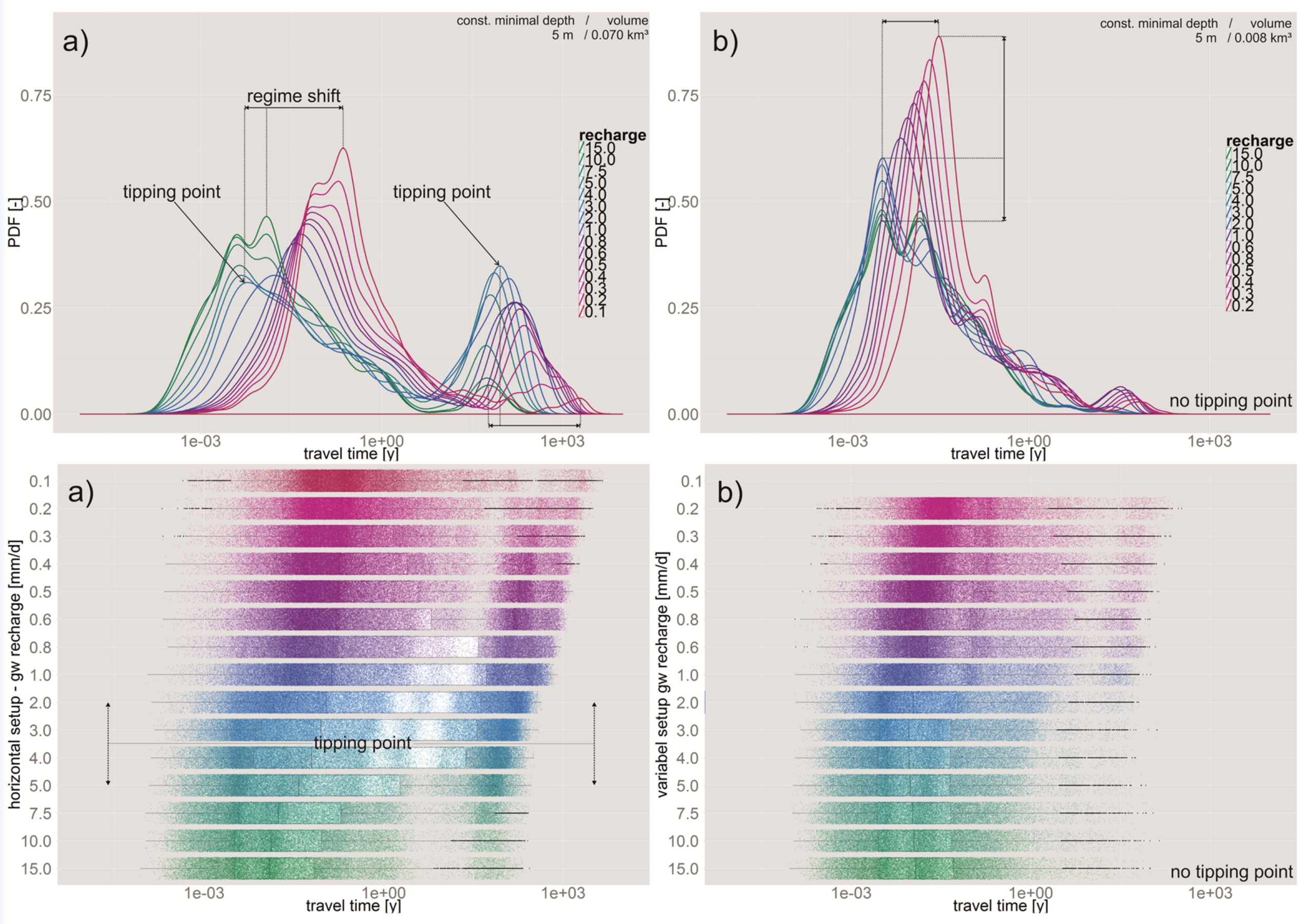
[4] R Core Team (2012). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL: http://www.R-project.org/.

[5] Wickham, Hadley. "ggplot2: An implementation of the grammar of graphics." R package version 0.7, URL: http://CRAN. R-project. org/package= ggplot2 (2008).

4 Results

Steady state simulations

RTD spans particle ages from hours to serveral years showing complex shapes depending on groundwater recharge and geometry setup



a) horizontal domain bottom:

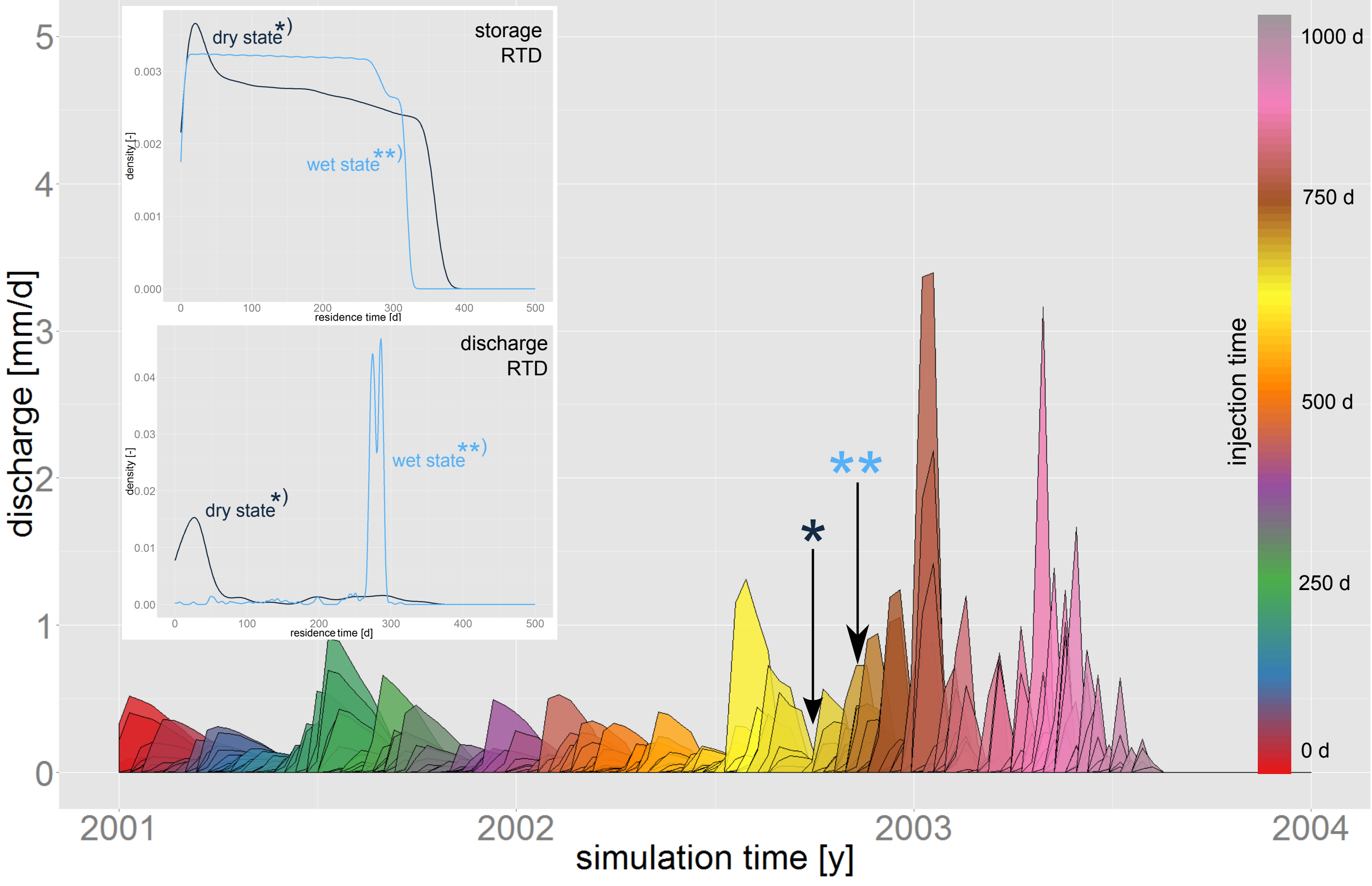
- High groundwater recharge rates predominantly result in unimodal RTD's and low variances
- A decrease of groundwater recharge activates longer / slower flow paths which results in bimodal structure and higher variances
- Tipping point at medium groundwater recharge rates (ca. 3 mm d-1) indicates a regime shift to older age distributions
- Low groundwater recharge shifts back to unimodal behaviour and low variances

b) variabel domain bottom:

- Unimodal behaviour present for all groundwater recharge scenarios, constant variances, no tipping point observable

Transient simulations

Transient RTD reveal injection time dependent particles ages up several hundred days with rather simple shapes. However, just a small fraction of the total injected particle amount can be retrieved (up to 25%) within the captured time period. The rest remains in the catchment storage and are released in later stages.



Depending on the pre-event state of soil moisture and groundwater level a specific precipitation event can reveal varying complex RTD' shapes:

- High precipition rates and wet states (high groundwater level) result in relatively long particle paths
- Precipitation events during dry states (low groundwater level) result in shortend paths
- Longer particle paths may form a significant contribution to baseflow periods
- transient behaviour much more complex then steady state

5 Conclusion

Complex RTD's have been obtained for steady state and transient model solutions. They were used to test parameter fields, model geometries and time series independently.

Steady state results indicate a strong influence of model geometry and groundwater recharge rates on RTD's characteristic:

- varying groundwater levels activate different subsurface flow paths
- mean travel time and variances differ significantly for changing volumes and recharge rates

The transient results of dynamic RTD's reveal a complex non-linear interrelationship between the temporal change of hydrological states (e.g. pre-event discharge, soil moisture, groundwater heads, etc.) and the probability of an individual water parcel to leave the catchment / storage.

Future particle tracking analysis will concentrate on particle age distributions in storage, evapotranspiration and their relation to discharge age distributions.

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