Modelling Groundwater Travel Time Distributions in the Hainich CZE

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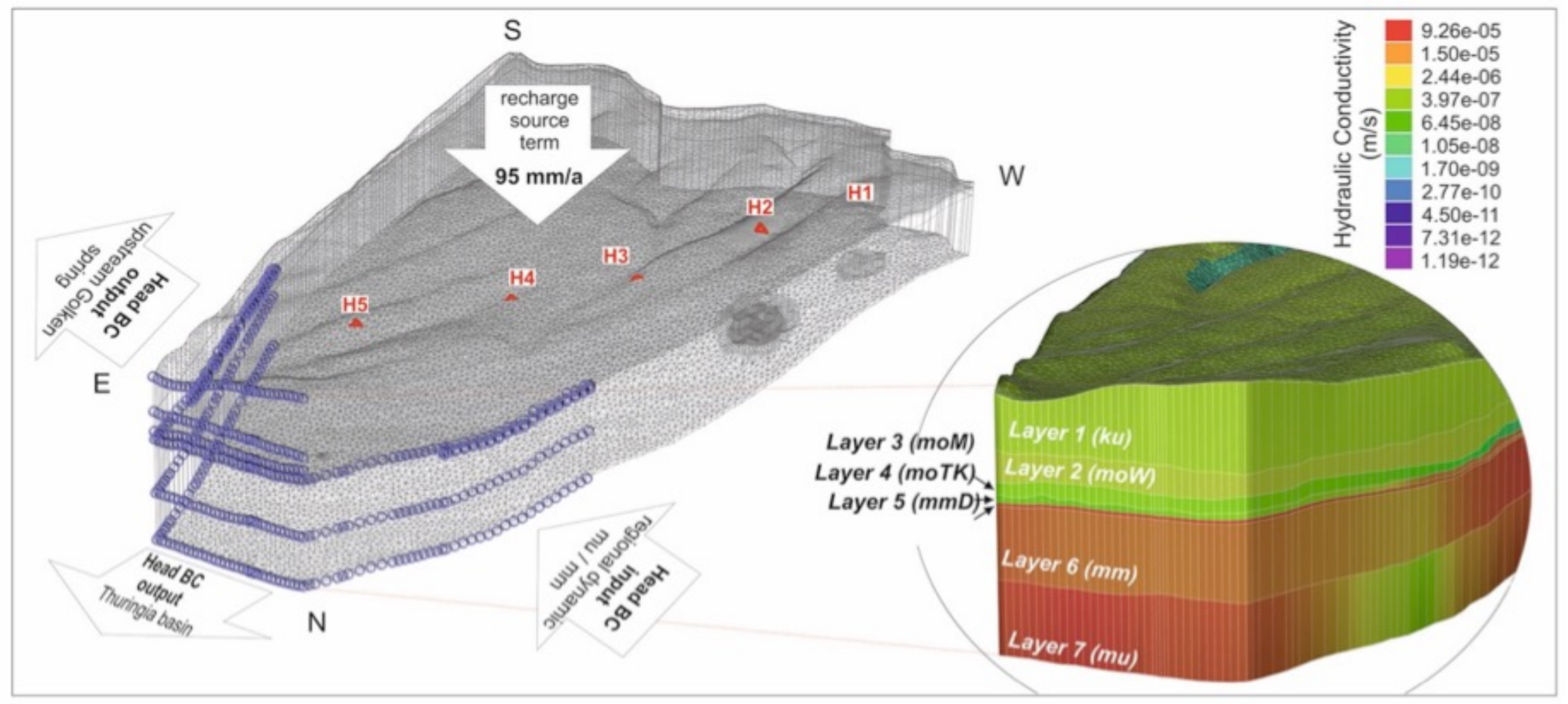

Fig. 1 Numerical Groundwater Model of the Hainch CZE (Rödiger et al., in prep.).

Methodology

We released a total amount of 31.500 particles at 63 different time steps, each with a static vector field from the model forced by temporal fluctuating recharge as well as varying constant head boundary conditions. The particles were appointed at each well in the CZE starting at the depth of the screen and following the advective flux reversely. In order to account for dispersion and diffusion the random walk method was chosen. We identified the origin of the groundwater as tips of the streamlines over all times and for each well individually. Finally, the travel times for every time step and for each well were plotted, averaged and fitted with a gamma distribution to obtain a representative travel time distributions for each well.

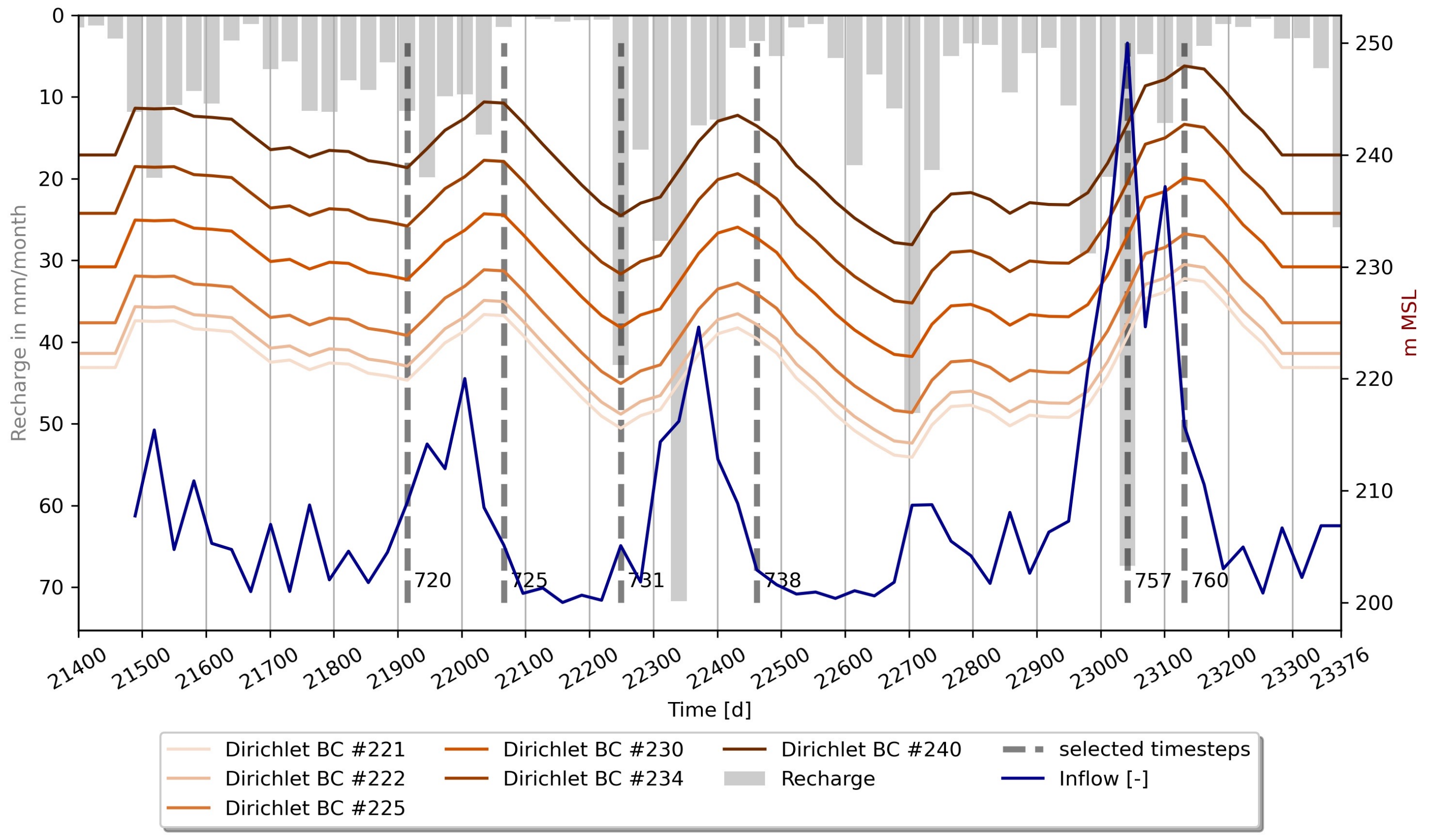

Fig. 2 Time series of recharge, dynamic gw head BC and net inflow.

Streamline Evolution

We found that the sensitivity of the travel time distributions depends on the magnitude and orientation of the advective flow field, thus resulting in a high variability throughout the investigated time steps (1 month). This is caused by temporal fluctuations of inflow (recharge from the surface and lateral inflow) as well as spatially heterogeneous hydraulic conductivities. Figure 2 depicts the temporally varying recharge, the dynamic head boundary conditions (Dirichlet type) in the North-West of the model (Fig. 1) and a resulting net inflow time series. Figure 3 visualizes the resulting streamlines for six different time steps (a – f) observed from the side (top) and from top (bottom). When the lateral inflow is high, the streamlines from well H5 are strongly influenced, i.e., they get longer, reach deeper and connect to larger areas of the model leading to longer travel times.

Introduction

The Hainich Critical Zone Exploratory (CZE) is located in the north-west of Thuringia in central Germany and serves as a large-scale natural lab to observe surface and subsurface processes. In order to understand the hydrogeological system, it's major pathways as well as the flow rates and travel times in coherence with the surface input signal, we have established a numerical groundwater flow model of the Hainich CZE (Fig. 1, Rödiger et al, in prep.) following the transect of the observation wells (H1 – H5). This built up the basis for a detailed particle tracking analysis to estimate the distribution of travel times of groundwater which can help to estimate the biogeochemical activity and thus the degradation capability of microbes to chemical substances.

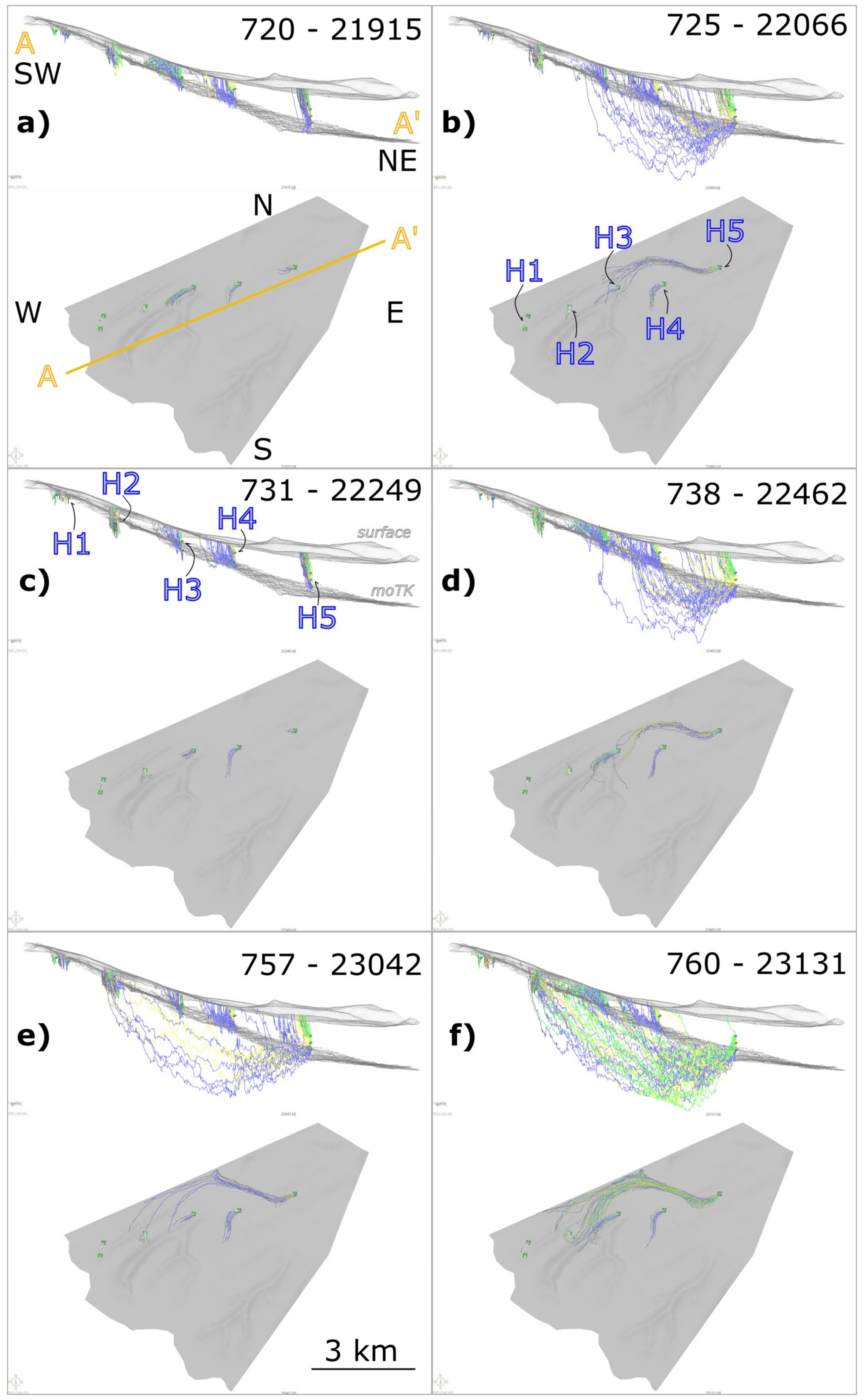

Fig. 3 Streamlines from side and top view for different time steps and wells.

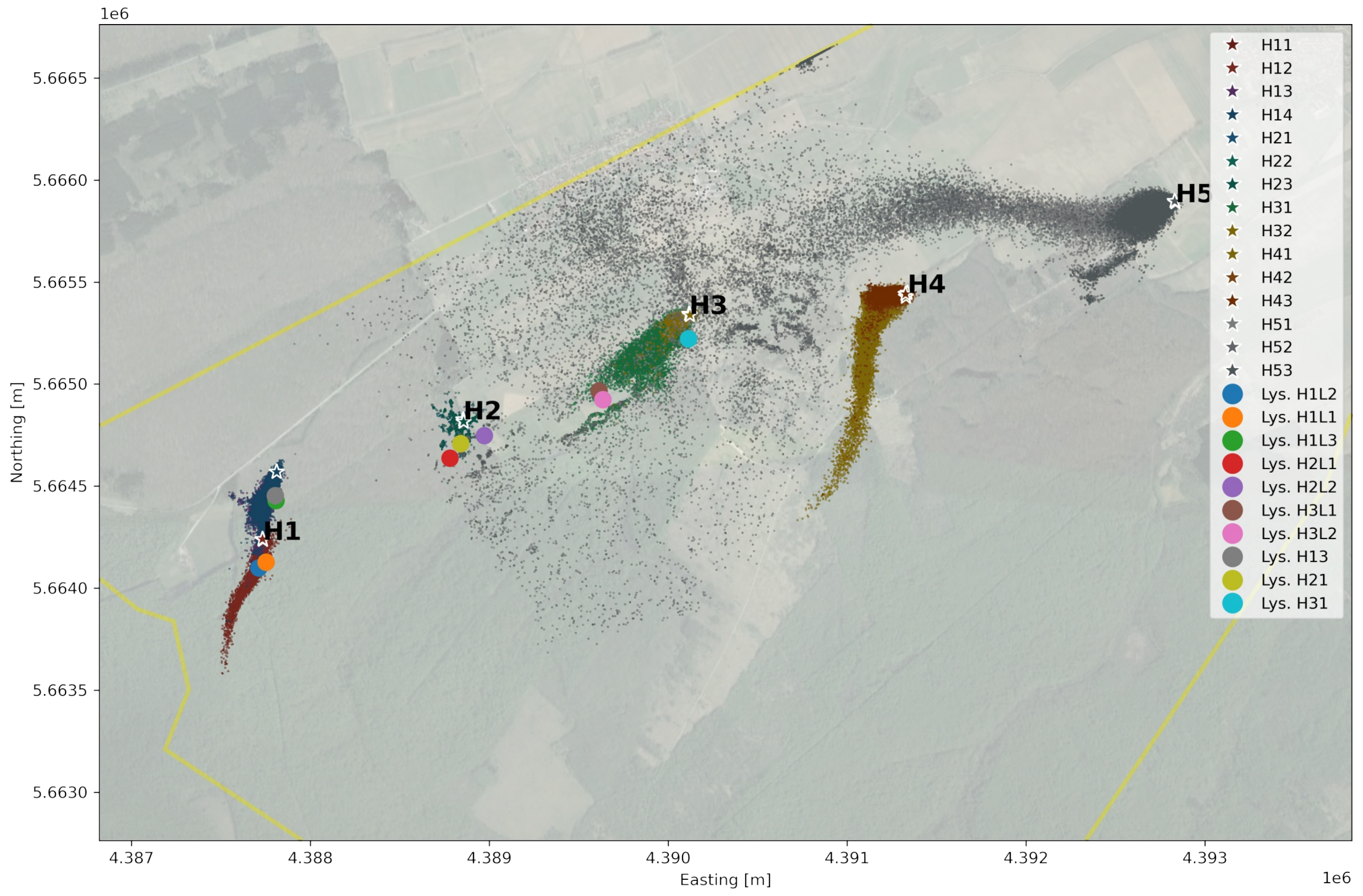

Fig. 4 Origin of particles which reached the wells for all time steps.

Tips of Streamlines

We extracted the tips of the streamlines, i.e., the location where the particles touched the model boundary and plotted them on a map in Figure 4. H1, H3 and H4 receive relatively local water with maximum distances of around 0.5 km (H1), 0.7 km (H2) and > 1 km (H4). Particles which reach the screen of H2 stem from areas which are located directly around the observation well, thus having a very local recharging area. The particle plume from H5 is in high contrast to the plumes of the other wells. It has a regional character with a size of roughly 4x2 km, consequently, draining water from upslope areas close to well H2 and H3 might end up in well H5 instead of H2 or H3. Hence, this demonstrates a possible connection of H2, H3 and predominantly deeper wells of H5 (H51, H52) under certain flow scenarios (Lehmann et al, 2020).

Travel Time Distributions (TTD)

We obtained a single distribution of the travel times for each well by weighing the distributions of each time step with the normalized net inflow into the model at that time step. Figure 5 depicts the normalized TTD for each time step and multiple wells as bars with colours from yellow to dark red. The weighted mean distribution is indicated with a black solid line. Travel time distributions are considered to have a shape similar to an exponential or gamma distribution (Haitjema, 1995, Jindal 2010). In order to account for variations in the data as well as to be able to quantify the moments of the distribution, we fitted the weighted mean TTD with a gamma probability density distribution of the form

$$f(x) = \frac{\beta^{\alpha}}{\Gamma(\alpha)} x^{\alpha-1} e^{-\beta x}$$

where $\Gamma(\alpha)$ is the gamma function, α is the shape and β is the rate (= inverse scale) parameter.

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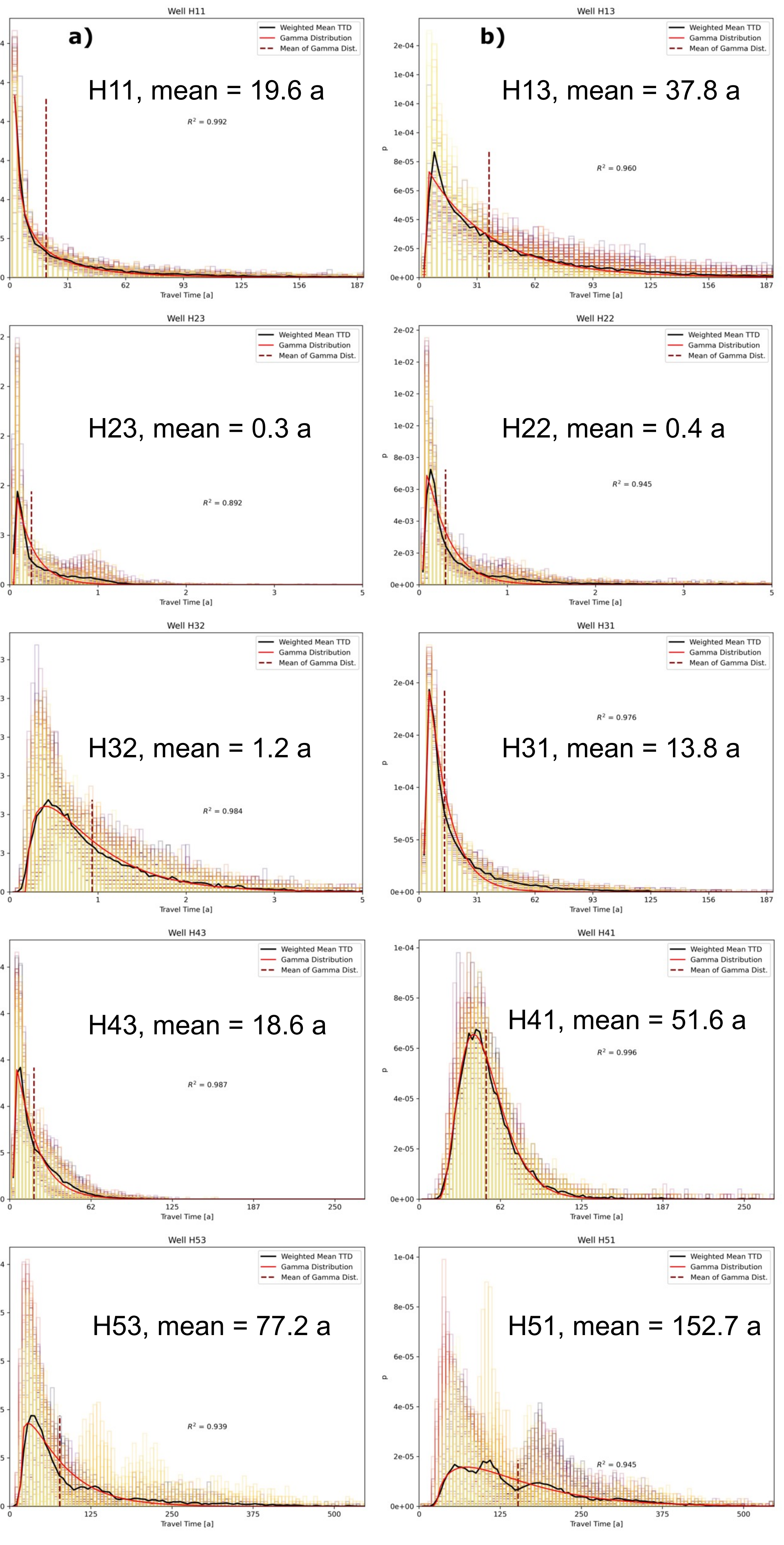

Fig. 5 Travel time distributions with fitted Gamma distributions.

H53 and H51 show a bimodal distribution which is caused by different flow pattern from dynamic boundary conditions (Fig. 2). Obtained TTD compare well to studies form Jing et al. (2019) and Nowak et al. (2017). They calculated travel times in the order of 100 – 200 and 295 – 403 years, respectively.

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