Spatio-temporal variations of high-degree mixing spots in a floodplain (assessed with a hydraulic mixing cell method)

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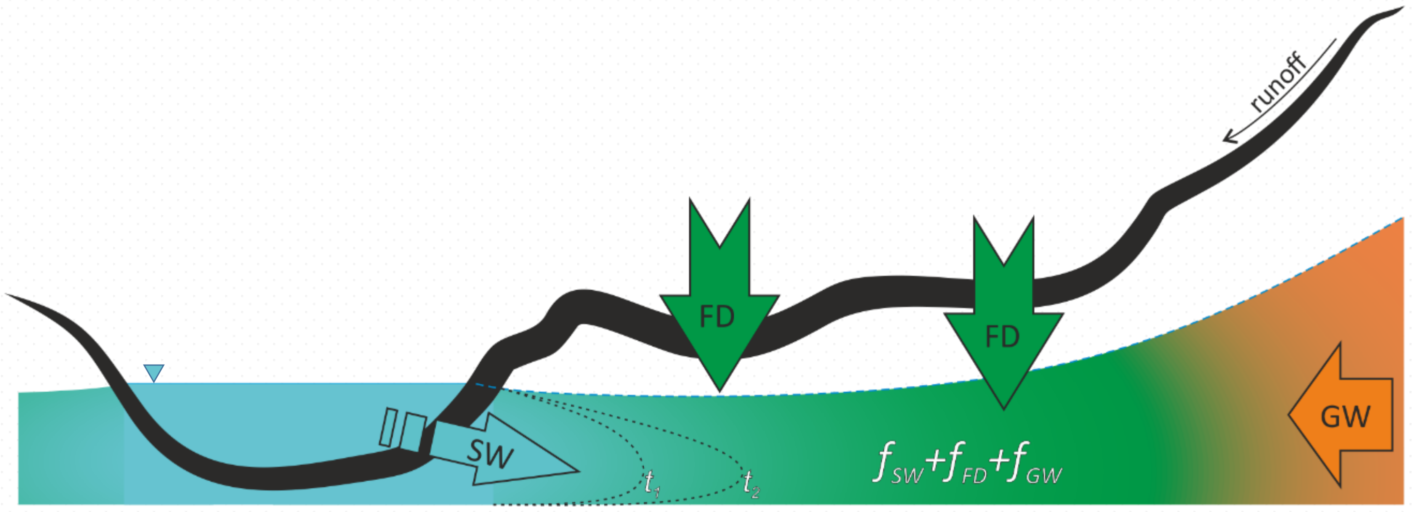
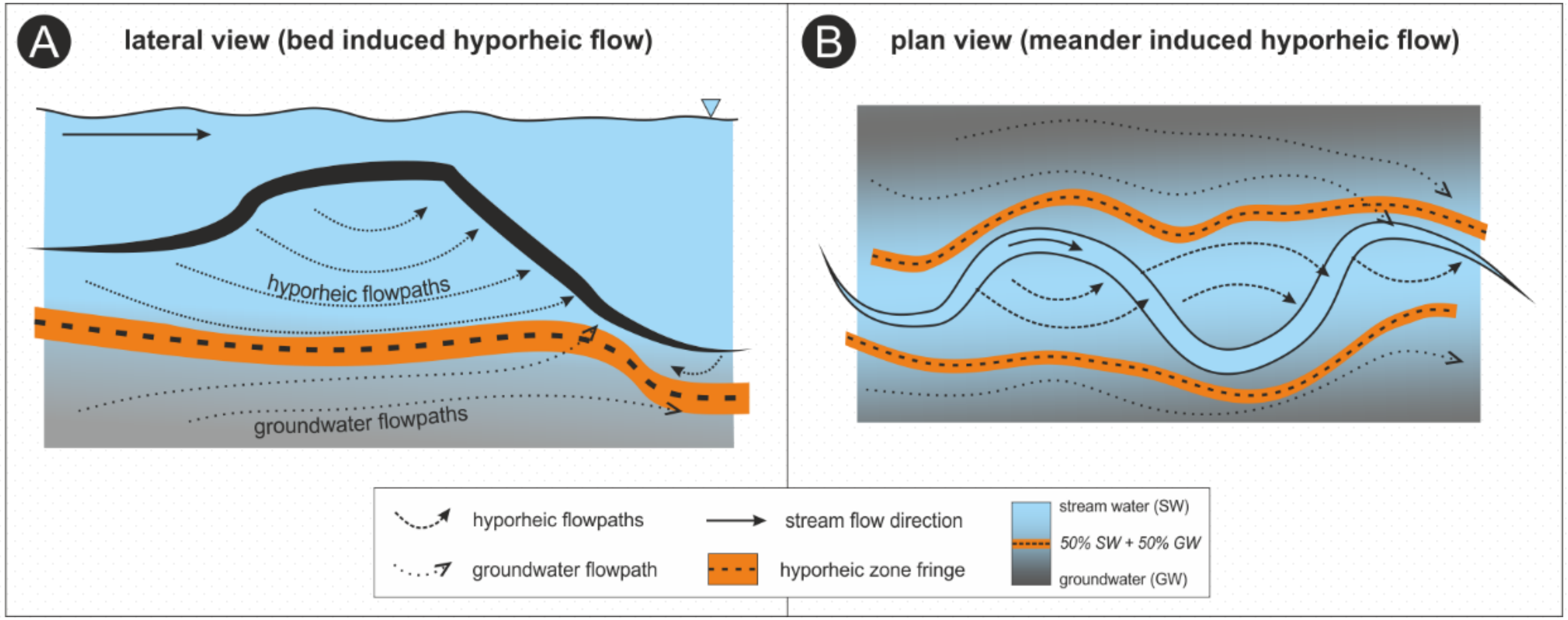


Why is mixing important?

Floodplain: mixing of different water sources, such as infiltrating stream water (*SW*); floodplain (rain/recharge, *FD*); and local flowing groundwater (*GW*).

Different solutes get in contact: higher potential for turnover of **groundwater-borne solutes** (e.g., NO_3^-).

Thus, mixing dynamics can control reactive potential of groundwater-borne solutes.



1.Introduction

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What has been done? What do we know?

- Directly quantification of mixing-dependent-denitrification below streambed: **Hester *et al.* (2013, 2014, 2019), Trauth *et al.* (2015), Trauth & Fleckenstein (2017)**

- Dynamics of the periheic zone (surficial fringe of HZ): **Berezowski *et al.* (2019)**
- Mixing and biogeochemical processes: **Jones *et al.* (2014), Stegen *et al.* (2016)**

- Mapping of different water sources at the floodplain (geostatistical/end-member models): **Lessels *et al.* (2016), Traut *et al.* (2018), Biehler *et al.* (2020)**

(time-labor demanding, may not capture full dynamics of processes)

What do we want to achieve?

- estimate different water sources at the flooplain and their variations;
- quantify and assess controls of (high-degree) mixing spots at the floodplain;
- assess their changes due to transient hydrological boundary conditions.

How?

Combine field-data and a fully-coupled flow numerical model (HGS);

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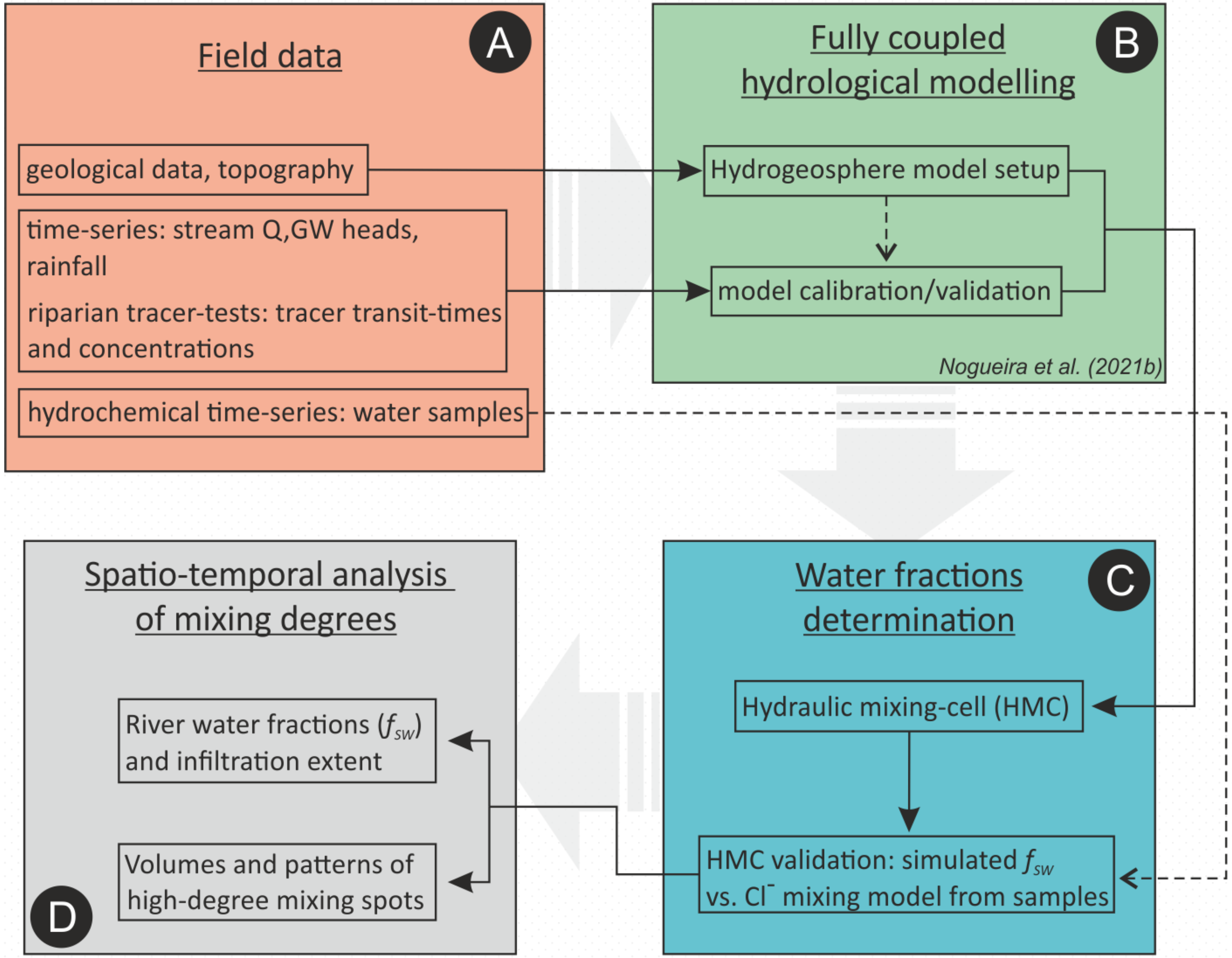
The spatio-temporal tracking of water parcels and their composition with a hydraulic mixing cell (HMC).

2.Methods – HGS-HMC method



A) Field data acquisition

B) *HGS* flow model setup and calibration/validation (*Nogueira et al. – under review*)

C) 1) *HGS-HMC* for tracking water parcel sources and composition (in each model cell and time-step);
2) HMC validation (f_{SW} x $\mathbf{F_{RIV}}$ on wells);

D) Spatio-temporal analysis of water fractions and mixing at the floodplain

2.Methods – HGS-HMC method

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HMC - *Hydraulic mixing cell* (*Partington et al.,* 2011, 2013)

- Water fractions calculated according to water fluxes and exchanges (based on flow solution - does not require any extra parameters)
- Predefined water sources/regions (e.g., rain, stream water, groundwater, seawater).
- Usually, all model nodes are initialized with an artificial "*initial*" fraction of 1.

Sources' fractions mixed according to volumes of different water fluxes into/out of a cell. For a time ***t*** and a fraction ***w*** within cell ***i***:

$$f_{i(w)}^{t} = \left(\frac{V_i^{t-1}}{V_i^t} - \frac{\sum_{j=1}^{m} V_{ij}\Big|_{t-1}^{t}}{V_i^t} \right) f_{i(w)}^{t-1} + \frac{\sum_{j=1}^{n} V_{ji}\Big|_{t-1}^{t} f_{j(w)}^{t-1}}{V_i^t}$$

water fraction *w* at cell ***i*** | water fraction *w* leaving cell ***i*** *to cell* ***j*** | water fraction *w* flowing from cell ***j*** *to cell* ***i***

with ***m*** sinks and ***n*** sources for cell ***i***

Predefined HMC water sources

- Stream water (f_{SW})
- Groundwater (f_{GW}) + Floodplain water (f_{FD}) (water coming from model top)
- Initial groundwater (f_{GWi}) ← "warm-up" period to flush it out prior analyses

HMC validation

Comparison of simulated f_{SW} with calculated stream water fraction ($\mathbf{F_{RIV}}$) from Cl^- mixing model

$$F_{RIV} = \frac{[Cl^-_{obs}] - [Cl^-_{GW}]}{[Cl^-_{SW}] - [Cl^-_{GW}]}$$

HMC fractions integration

$$V_w = \frac{\sum_{p=1}^{P} f_w}{V_{tot}} \times 100\%$$

2.Methods – HGS-HMC method

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Mixing degrees (d)

$$d = 1 - \left[\frac{\sqrt{\left(\frac{1}{2} - f_{SW}\right)^2 + \left(\frac{1}{2} - (f_{GW} + f_{FD})\right)^2}}{\left(\frac{\sqrt{2}}{2}\right)} \right]$$

d=1 (“perfect mixing”) = equal HMC water fractions within a cell

high-degree mixing spot (d_h) = $d \geq 0.75$

High-degree mixing spots (d_h) integration

$$V_{d_h} = \frac{\sum_{p=1}^{P} d_h}{V_{tot}} \times 100\%$$

HGS flow paths extraction and transit-times calculation

Based on transient velocity-fields and particles positions (TecPlot+MatLab)

Particles released at the streambed and floodplain (≈1,300 per time-step)

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HMC fractions integration

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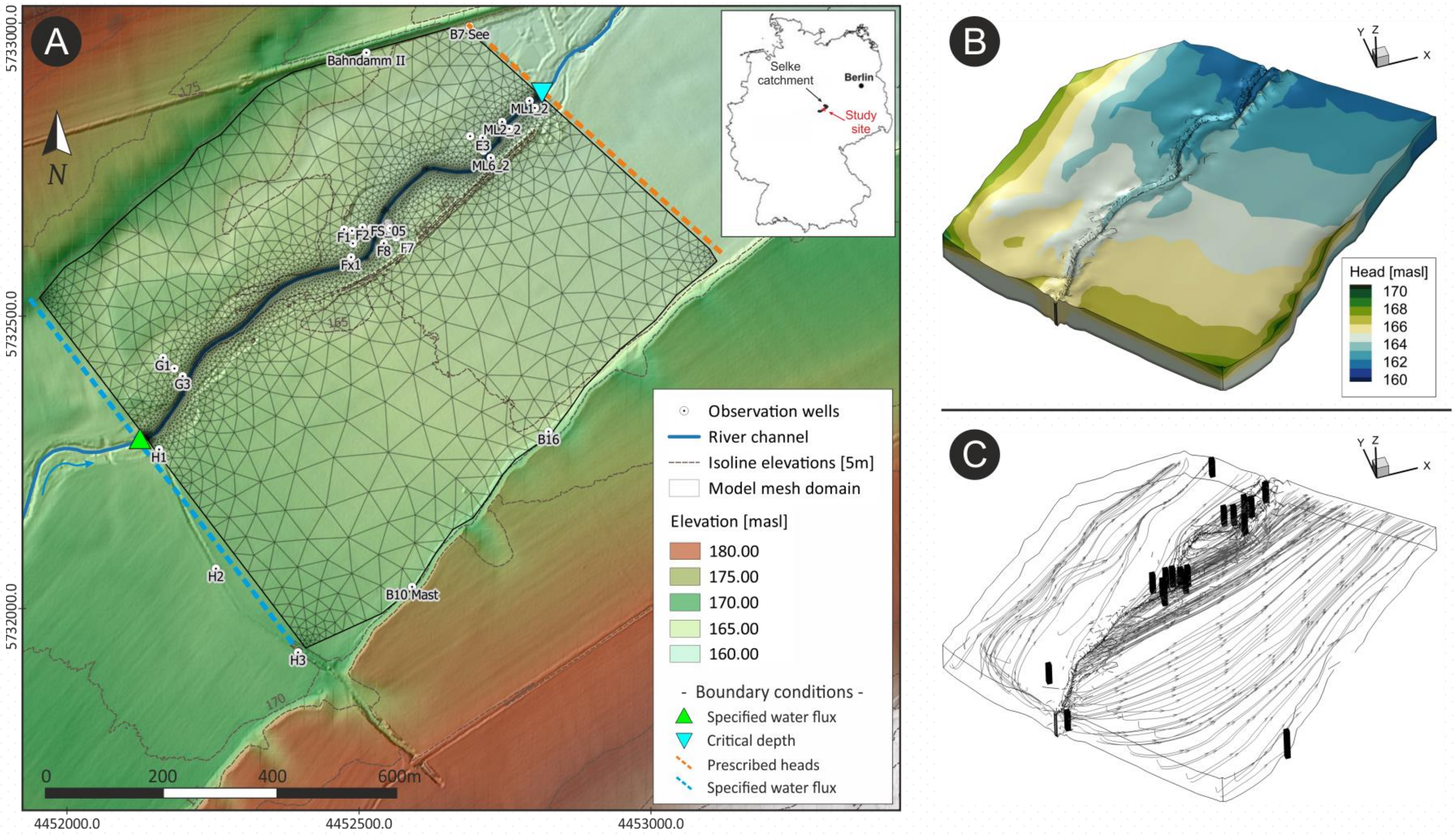
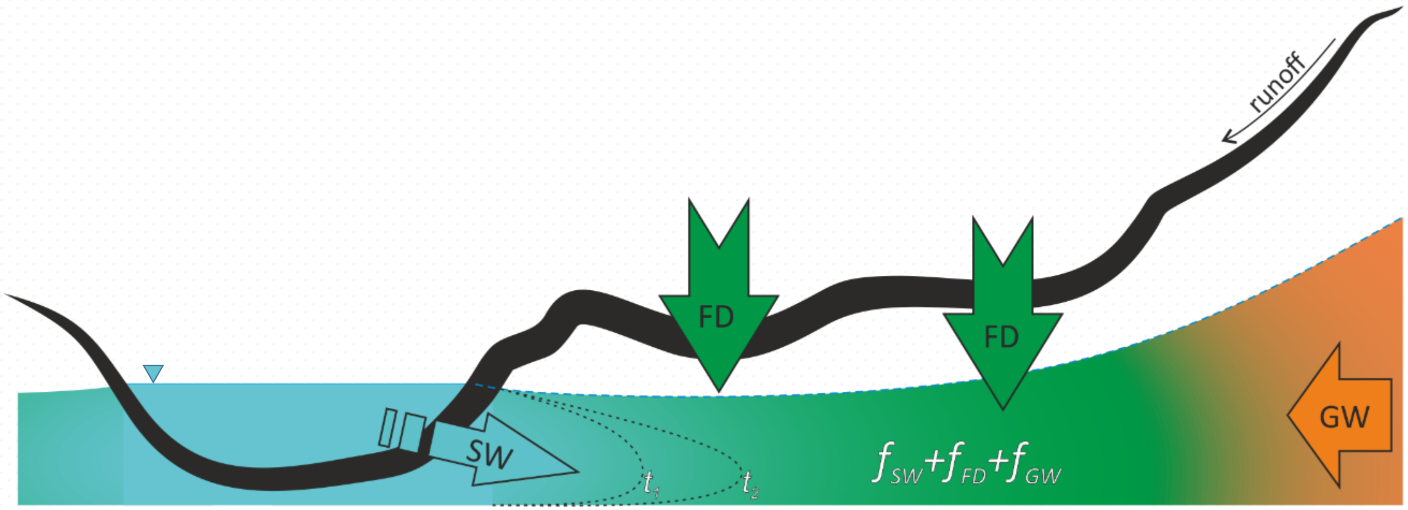
2.Methods – Case study and numerical model



Application of a pre-calibrated flow model (period 2017-2019) for a transient simulation between 2013-2016.

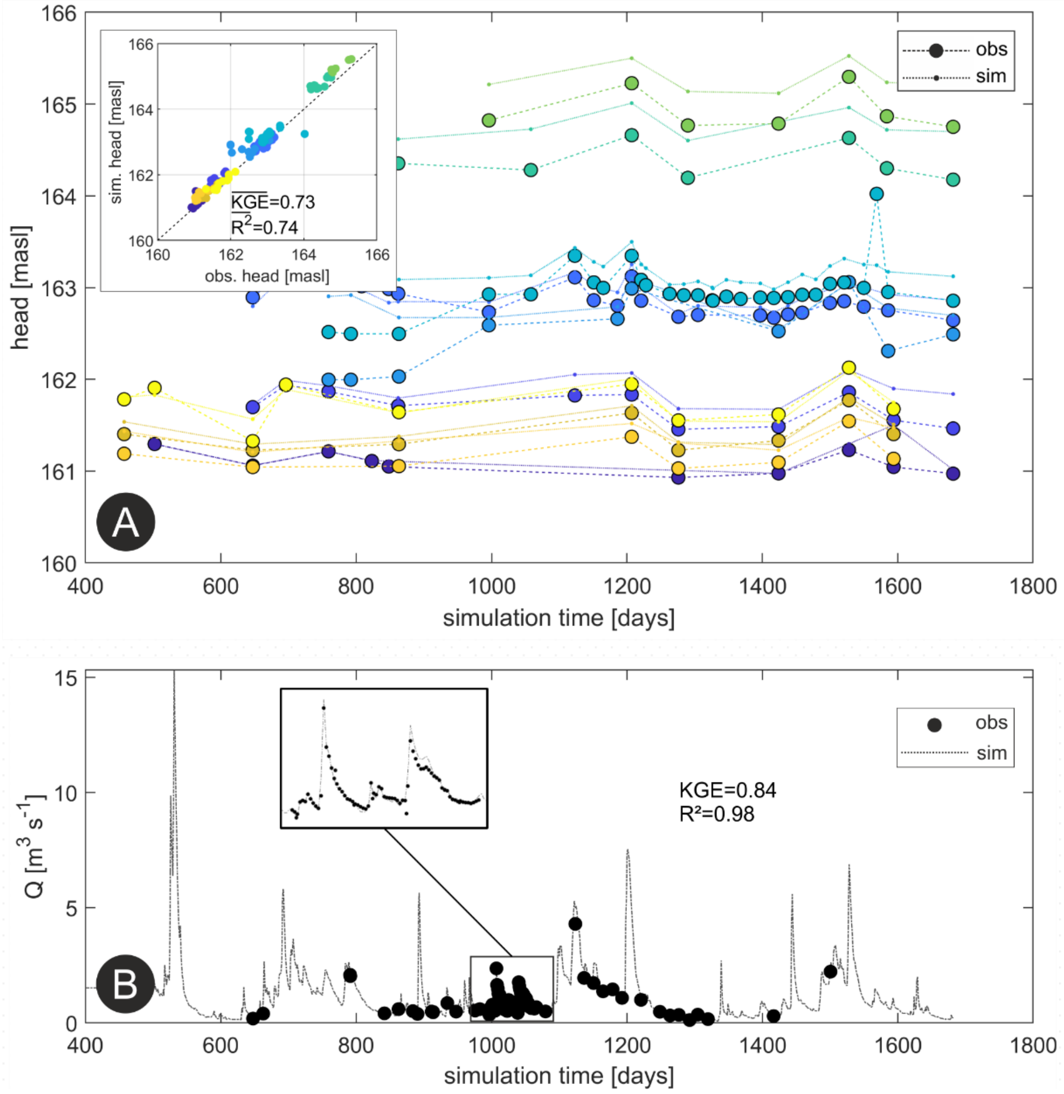
- Adjustment of flow boundary conditions
- & no additional calibration

3.Results

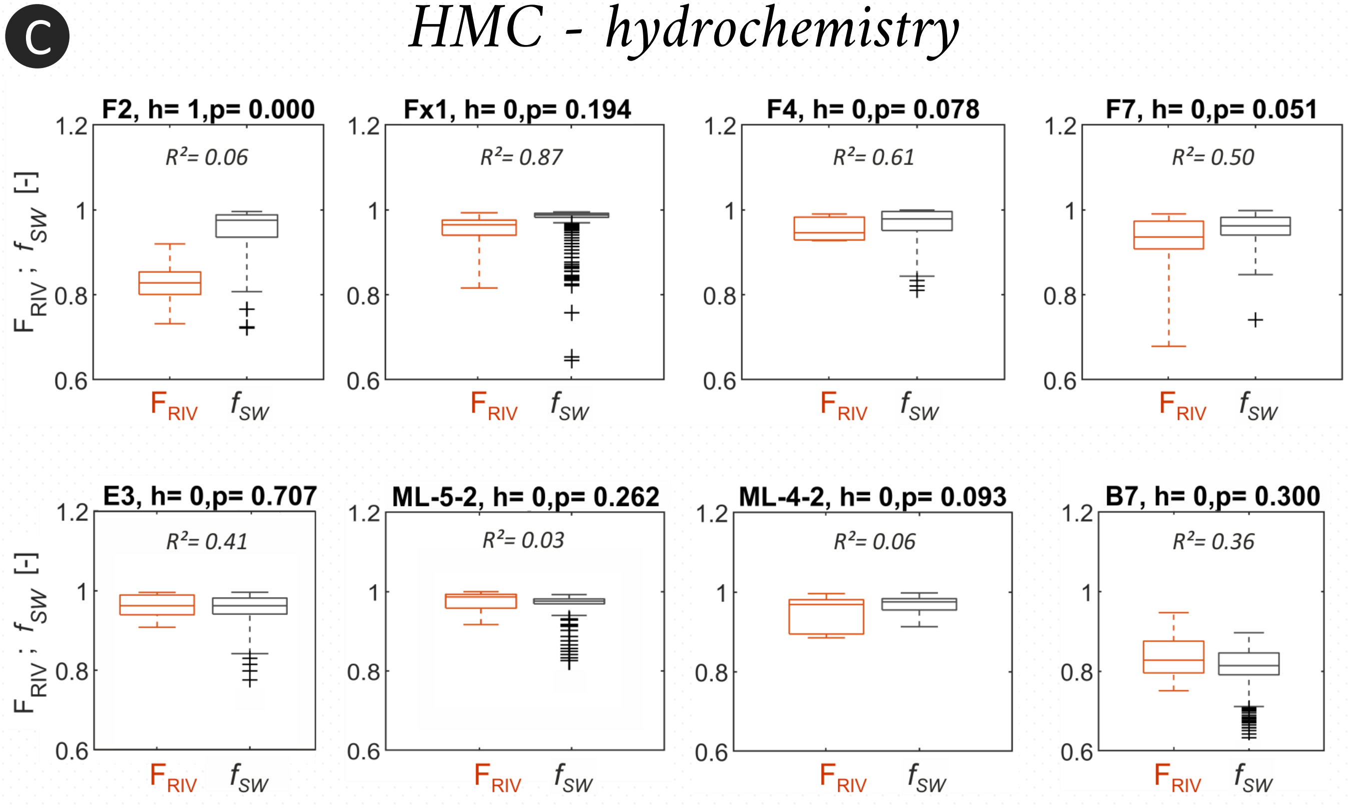


3.Results – Model/framework validation

HGS - flow



HMC - hydrochemistry

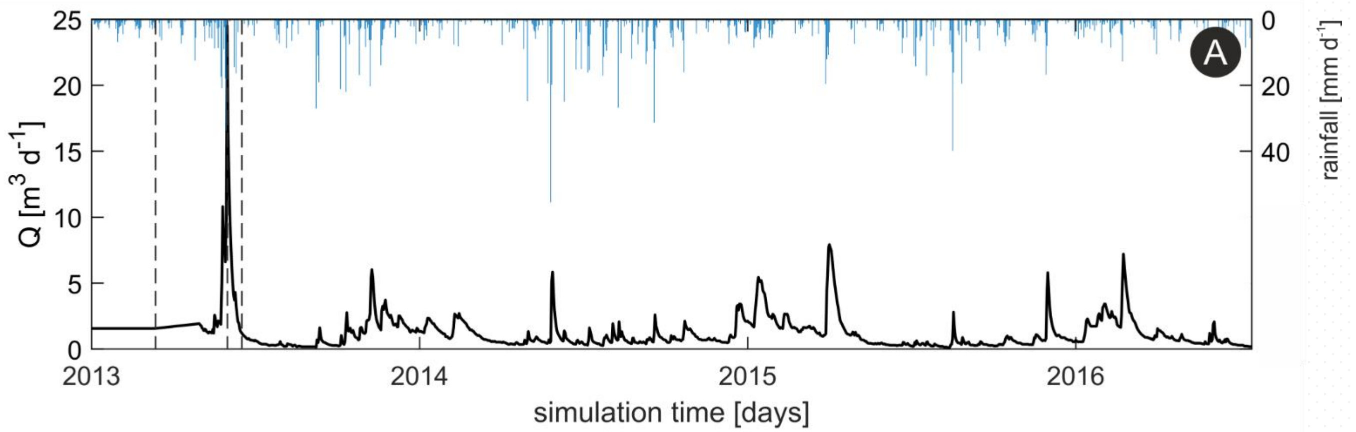


Calculated $\mathbf{F_{RIV}}$ and simulated f_{SW}

Wilcoxon-Test for groups medians (h=0, *p-value*); Correlation coefficient (R^2)

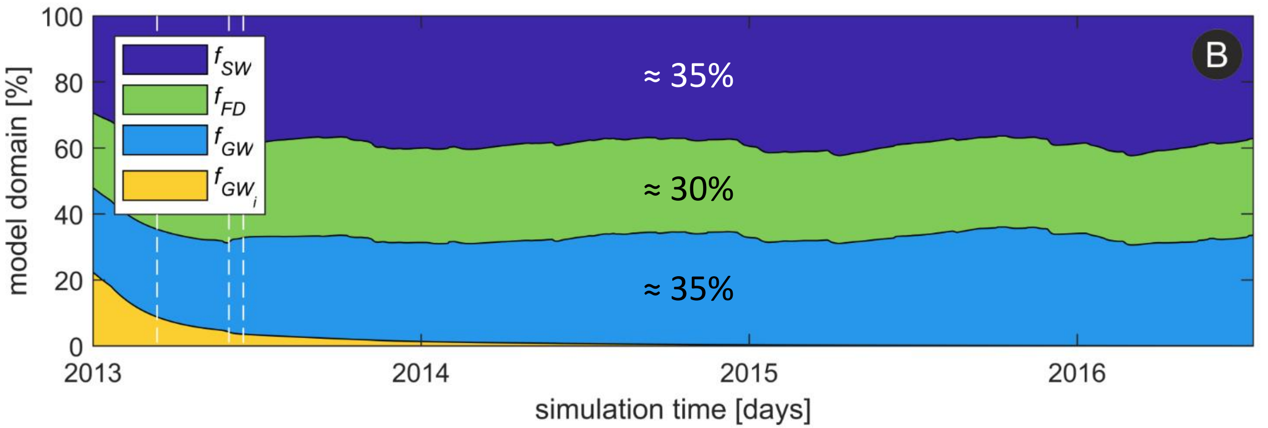
Acceptable differences since a rigorous calibration to hydrochemical data was not our goal

3.Results – Temporal variation of HMC fractions

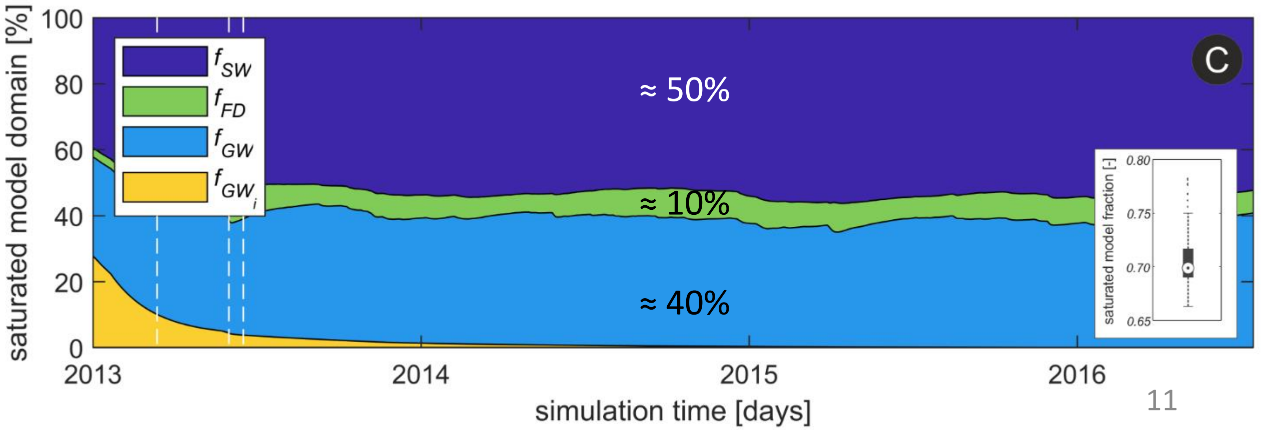


(B) HMC fractions for the entire domain

HMC results : water origin (*not the water content*!)



(C) HMC fractions for the fully-saturated domain



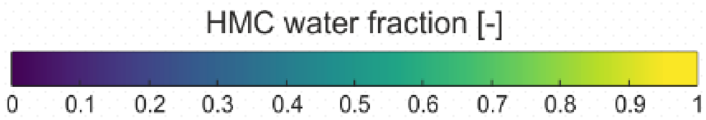
3.Results – Spatial distribution of HMC fractions

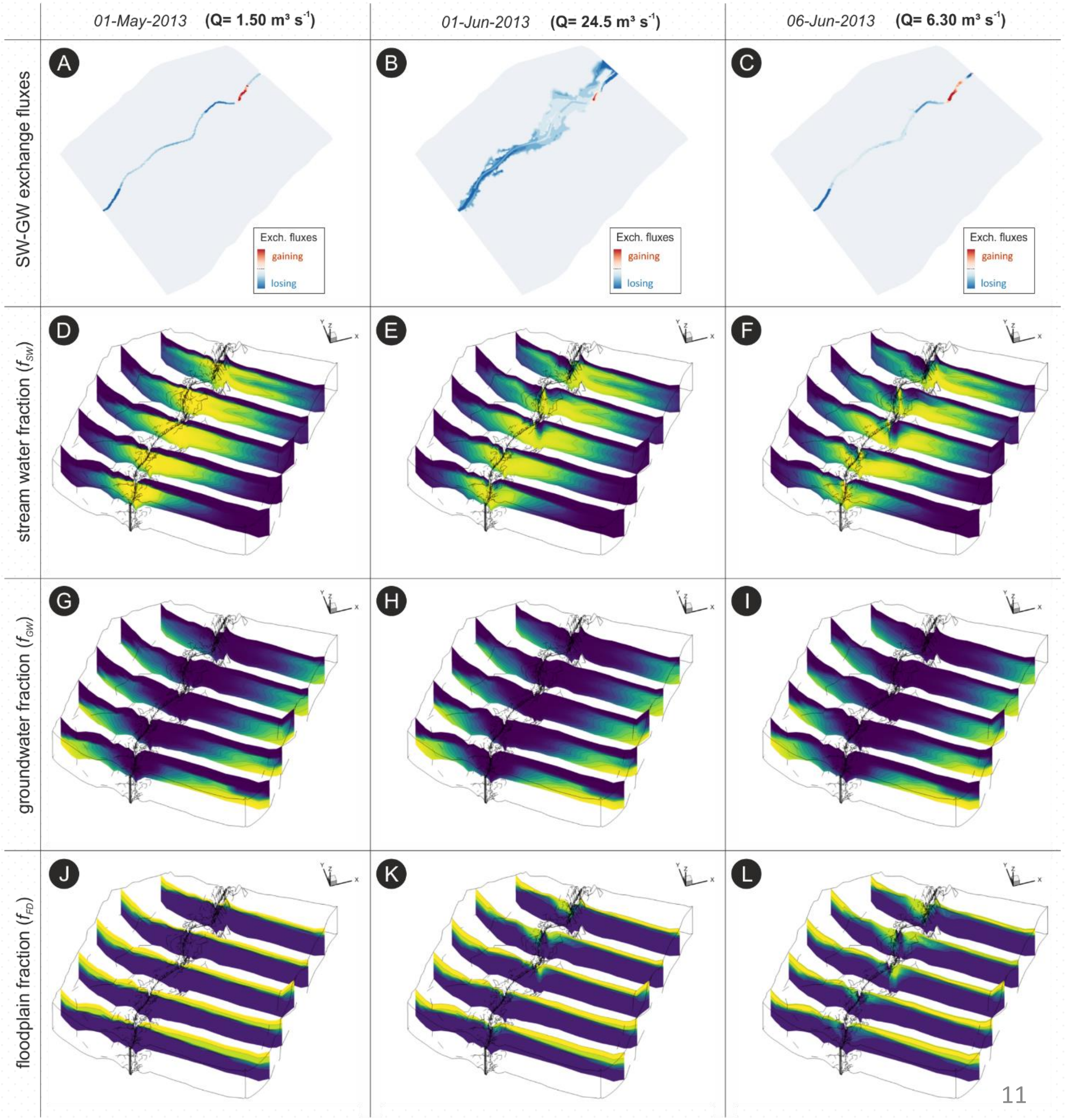
(A-C) SW-GW exchange patterns

(D-F) stream water (f_{SW})

(G-I) groundwater (f_{GW})

(J-L) floodplain water (f_{FD})



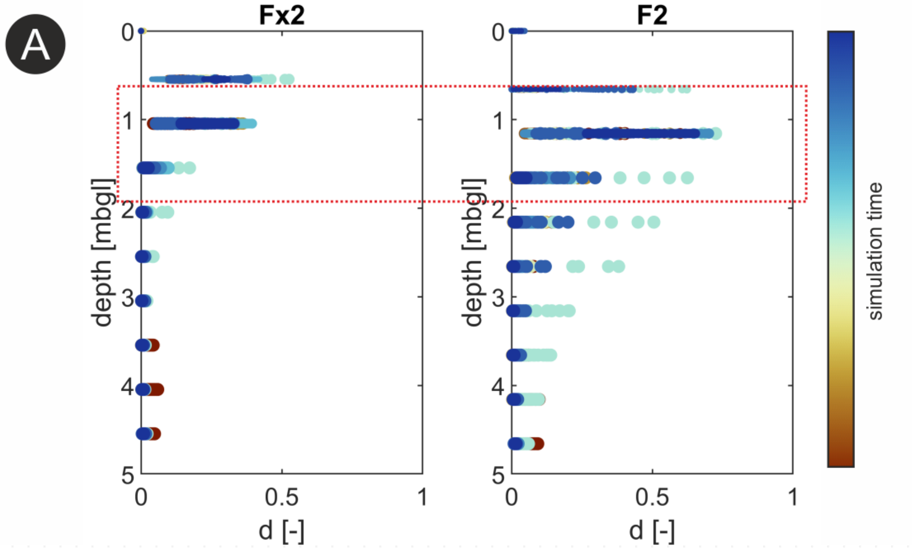


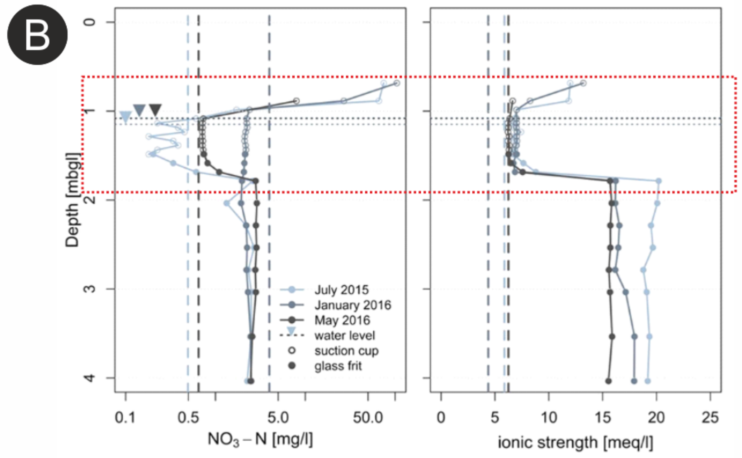
3.Results – Mixing degree: vertical variation

(A) Mixing degrees vs. wells' depths

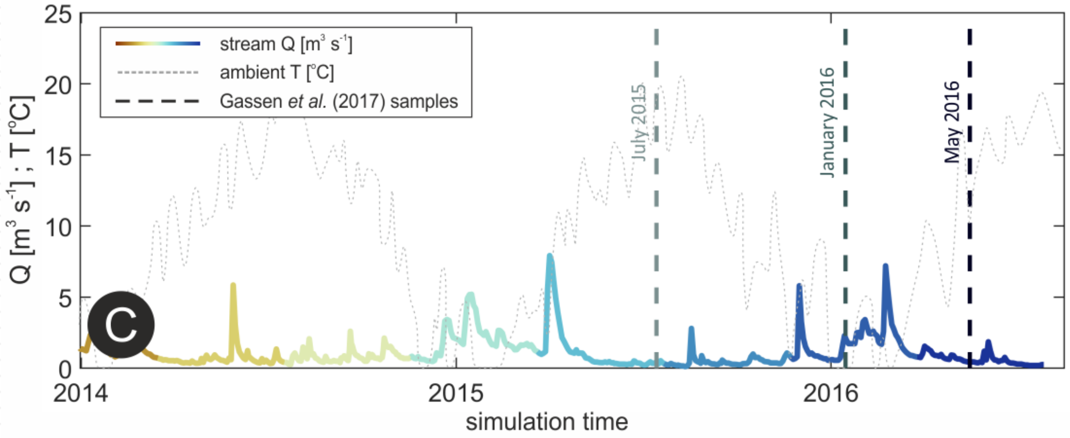
(B) NO_3^- concentration and ionic strength for a high-resolution obs. well (*Gassen et al.*, 2017)

(C) Stream Q and sampling of *Gassen et al.* (2017)





Gassen et al. (2017) *well: near Fx2 and F2*



Key point:

FD_NO_3^-

+

SW_DOC

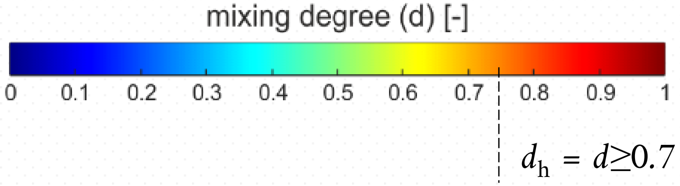
High NO_3^- "mixing-turnover"
(temperature controlled)

3.Results – Mixing degree: spatial distribution

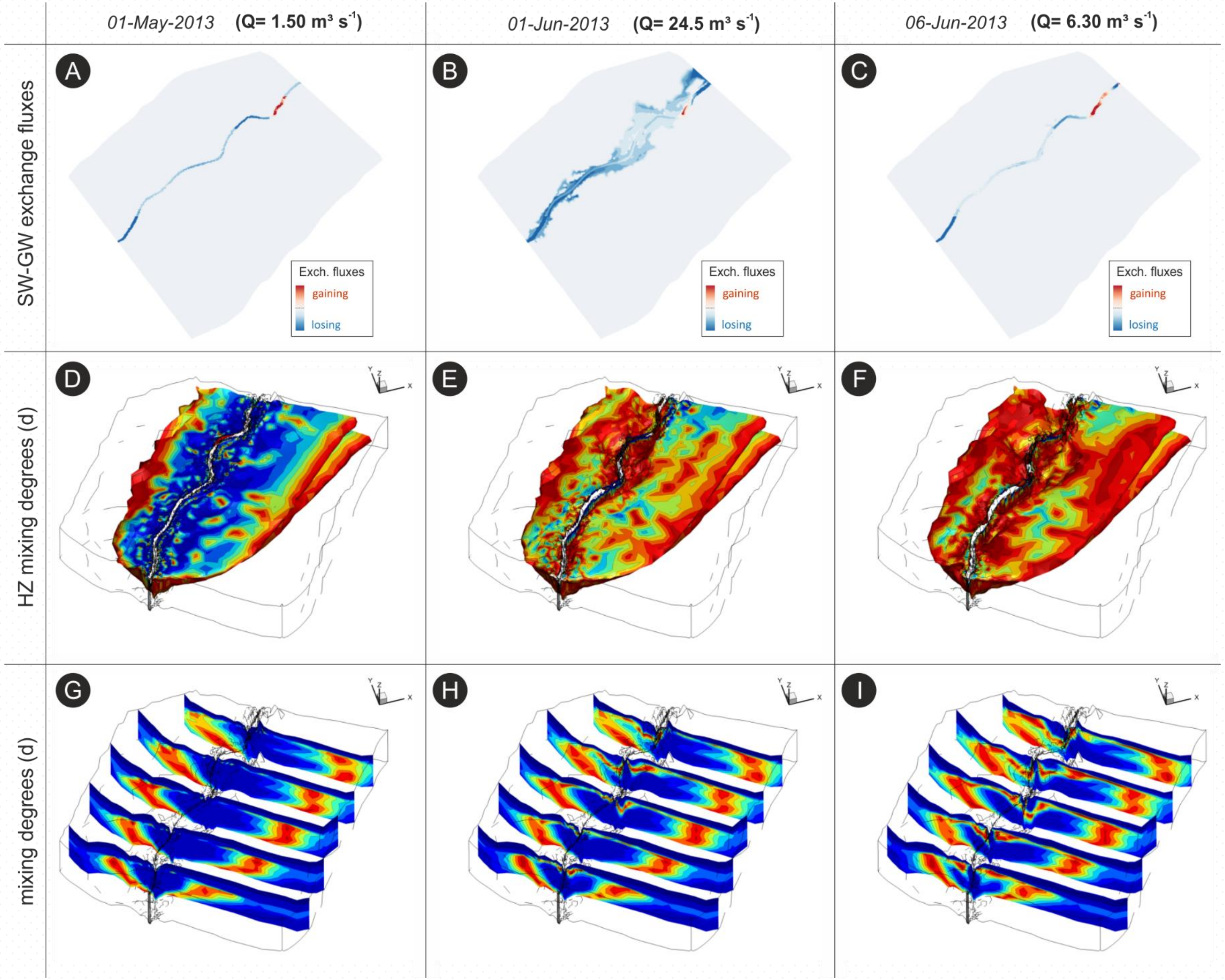
(A-C) SW-GW exchange patterns;

(D-F) mixing degrees within the HZ ($f_{SW} \geq 0.5$),

(G-I) mixing degrees on the entire domain.



$d_h = d \geq 0.75$



Key point:

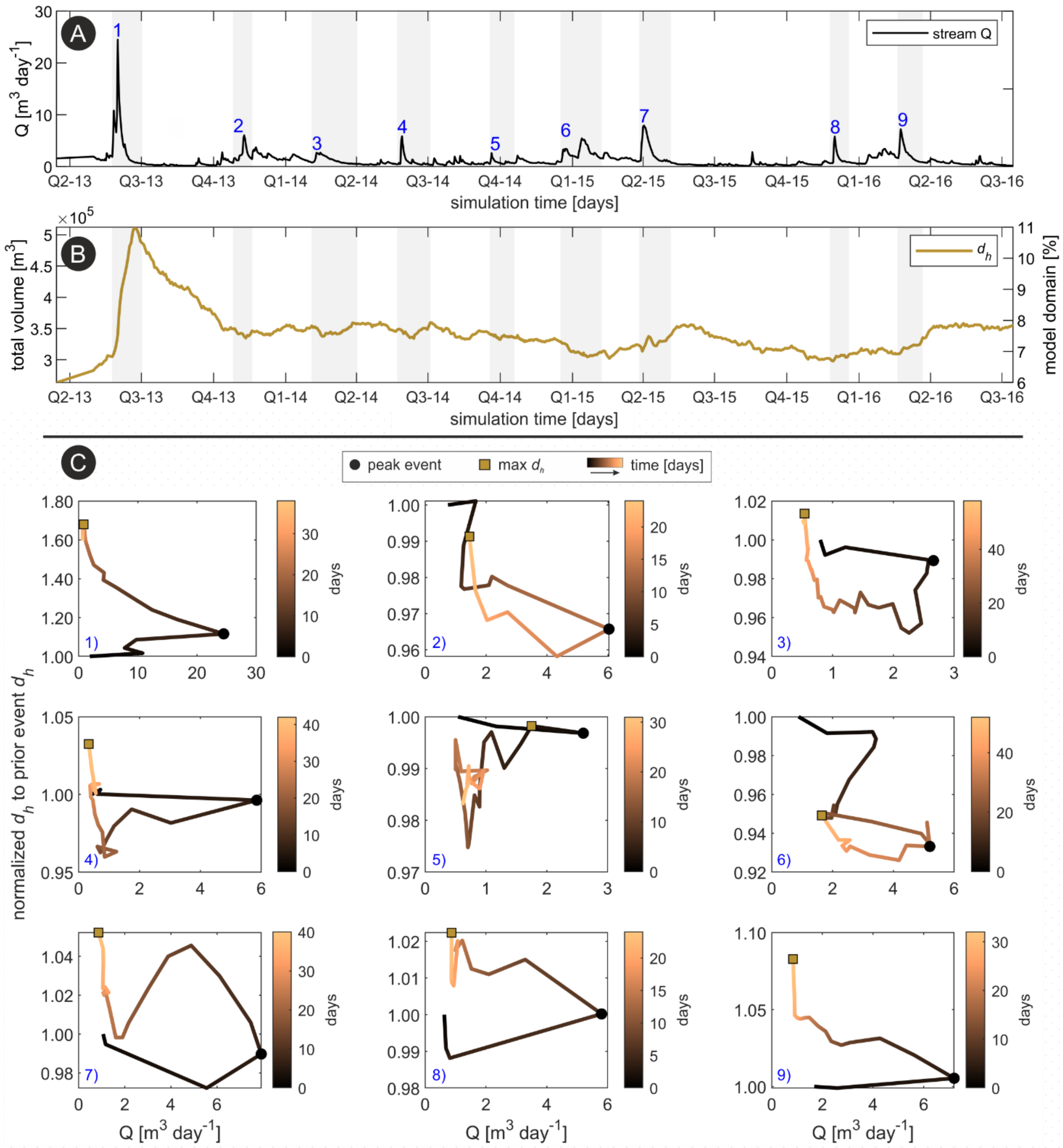
- Mixing mainly at the fringe of HZ, following Q events

3.Results – Temporal variation of high-degree mixing spots (d_h)

(A) Selected discharge events

(B) Total d_h volume (and % of domain)

(C) Q *vs. normalized* d_h plots for selected discharge events



Key points:

- Q events increase overall d_h (≈5%)

3.Results – Temporal variation of high-degree mixing spots (d_h)

(A) Selected discharge events

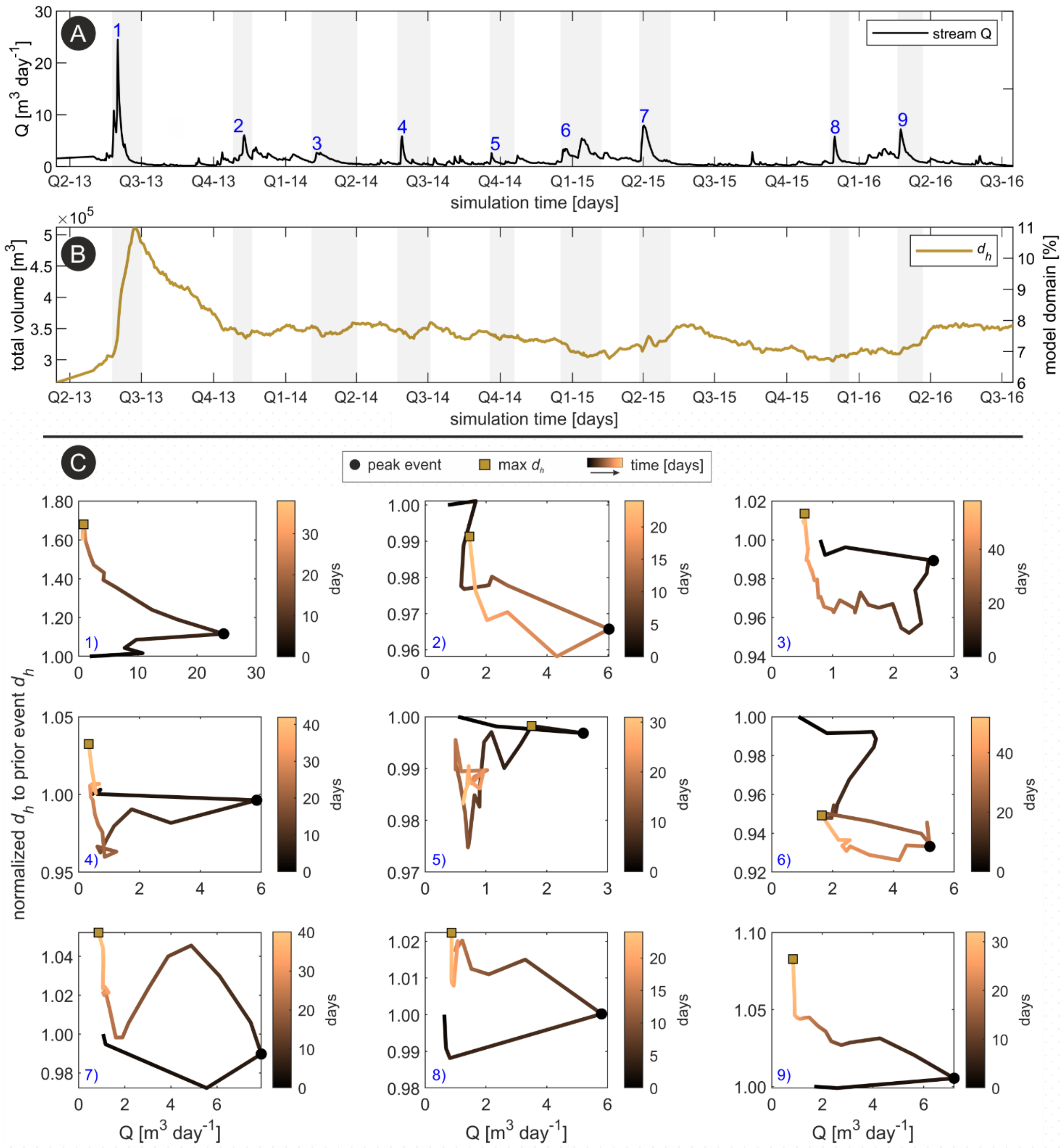
Table 1 – Overall Spearman's rank correlation between metrics of discharge events and the increasing of high-degree mixing spots (d_h) at the floodplain.

Discharge events metrics	Correlation to increase in d_h
Event duration [days]	0.009
Time-to-peak [days]	0.305
Time-to-peak/event duration [-]	0.340
Peak prominence (ΔQ) [m³ s⁻¹]	0.963

Lag between *peak-event* and peak d_h (after *peak-event*) [days]	
Min	1
Mean	14
Max	46

Spearman's correlation between ΔQ and lag to peak d_h: 0.28

Spearman's correlation between event duration and lag to peak d_h: 0.66



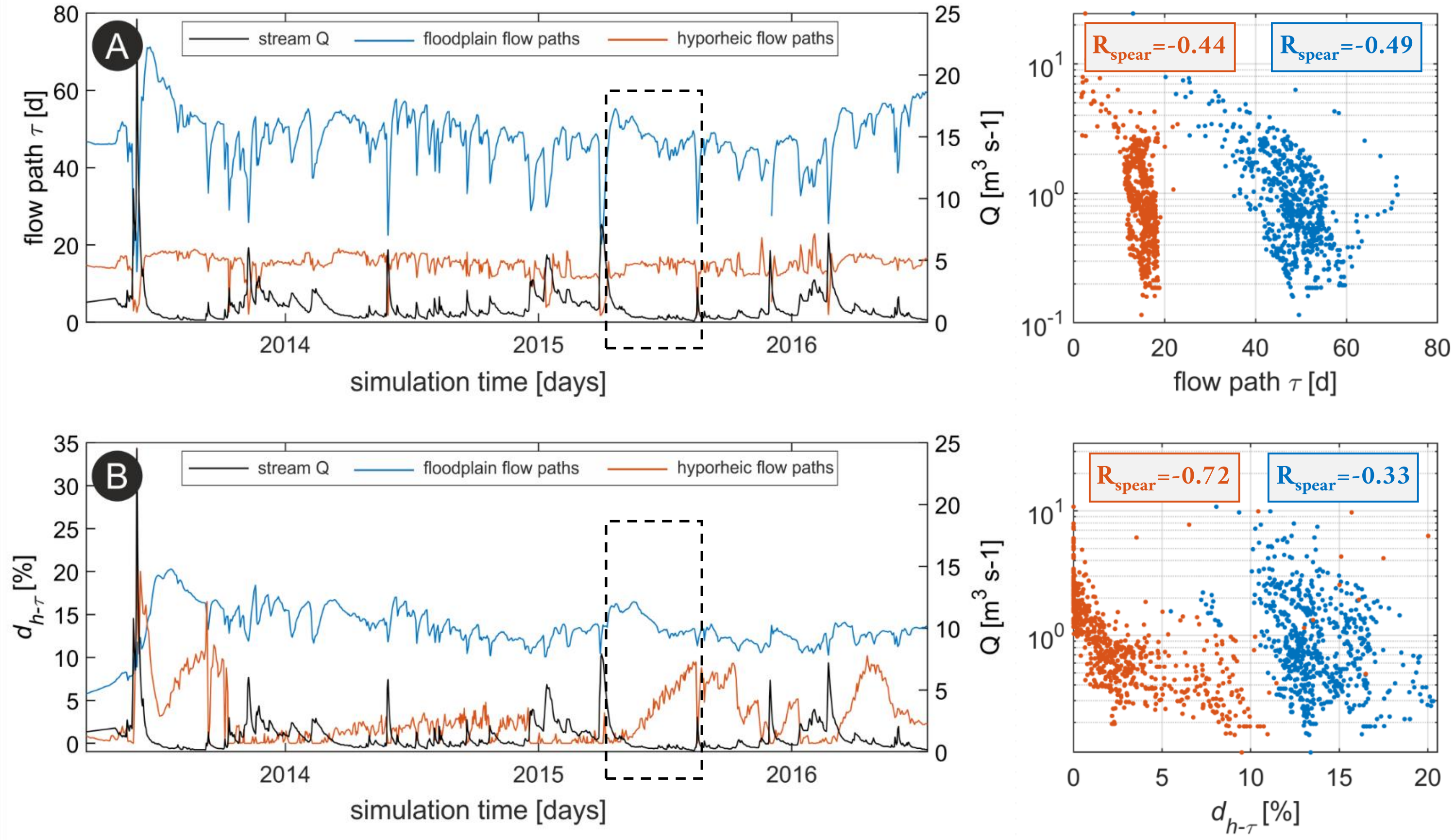
Key points:

- Q events increase overall d_h (≈5%)
- Peak prominence has the strongest control on increasing d_h
- Event duration has the strongest control on lag between Q peak and d_h

3.Results – Residence-time within high-degree mixing spots ($d_{h\text{-}\tau}$)

(A) Median flow path transit-times (flow path τ)

(B) Median residence-time within d_h zones ($d_{h\text{-}\tau}$) as a fraction of total flow path τ



Key points:

- Shorter transit-times during Q events (and also $d_{h\text{-}\tau}$)
- Hyporheic flow paths: greater $d_{h\text{-}\tau}$ during baseflow (slightly stronger gaining conditions -higher d_h) opposite to floodplain flow paths

Take home messages

Key message 1:

- *HGS-HMC* is an easy-to-transfer (straight-forward) tool for tracking different water-sources and their contribution at the floodplain scale

Key message 2:

- (high) Mixing mostly at the lateral fringe of the HZ, and at the groundwater table interface (mainly after flooding events)

Key messages 3:

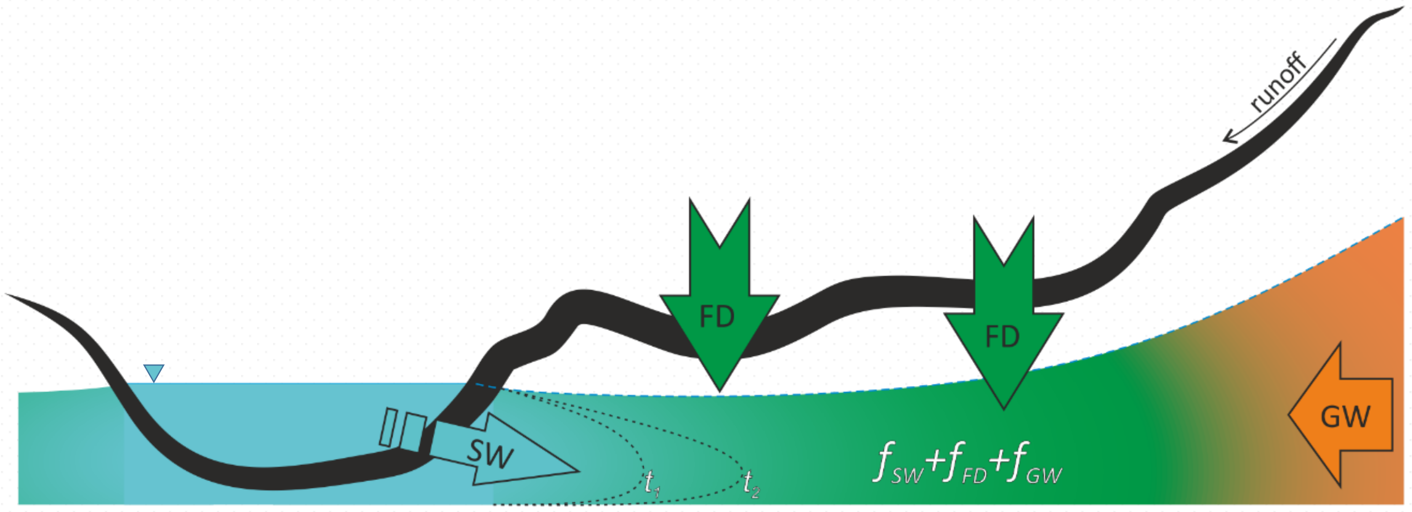
- Peak prominence has the strongest control on increasing mixing spots (on average 5% increasing, up to 50%)

Key message 4:

- Transit-times generally decrease during Q events (also does $d_{h\text{-}\tau}$); Discharge events seem to enhance "mixing-turnover" of groundwater-borne solutes at the floodplain more than at hyporheic regions.

Limitations:

- No simulation of reactions (or validation)
- No spatial distribution of HMC fractions within a cell
- Reliance on flow model solution



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Something else?

Thanks for the attention! :]

Mixing degrees: a vector in *w* dimensions

The distance between a "perfect mixing" point (V_p) and fractions in your node (V_n)

For 3 end-members (3D):

the perfect mixing:

Vp = [1/3, 1/3, 1/3]

the mixture:

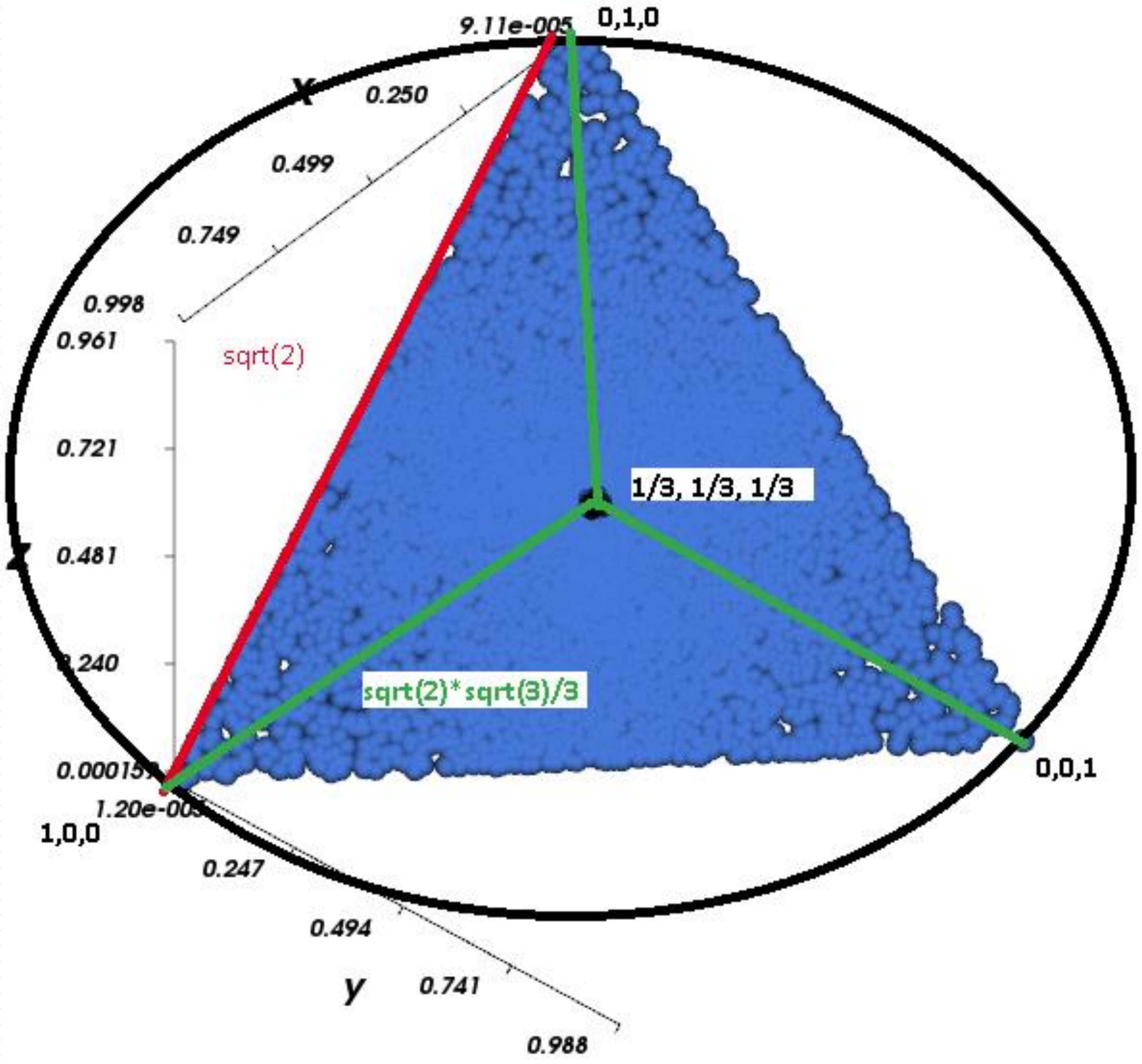
Vn = $[f_{SW}, f_{FD}, f_{SW}]$

distance between the two vectors:

dist = $\mathrm{sqrt}((x_p - x_n)^2+(y_p - y_n)^2+(z_p - z_n)^2)$

max_dist = sqrt(2)*sqrt(3)/3

d= 1-dist/max_dist

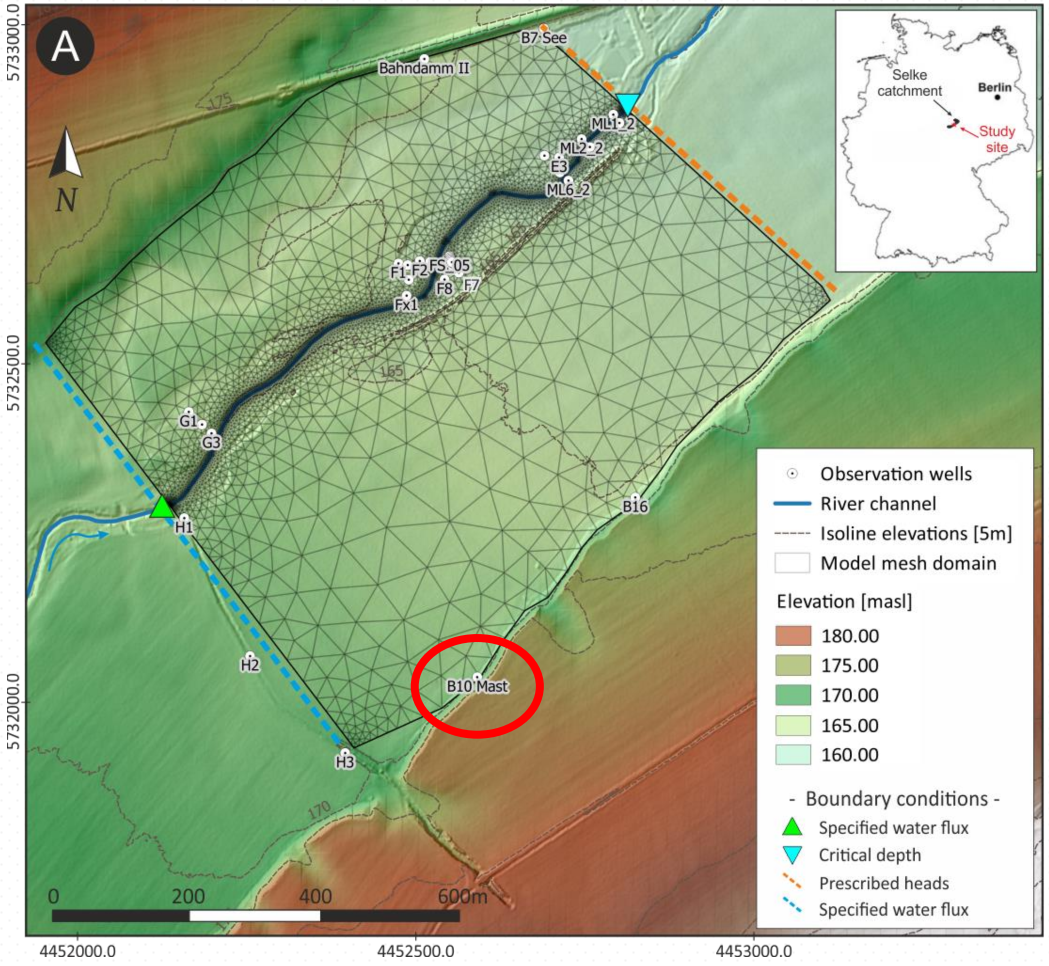


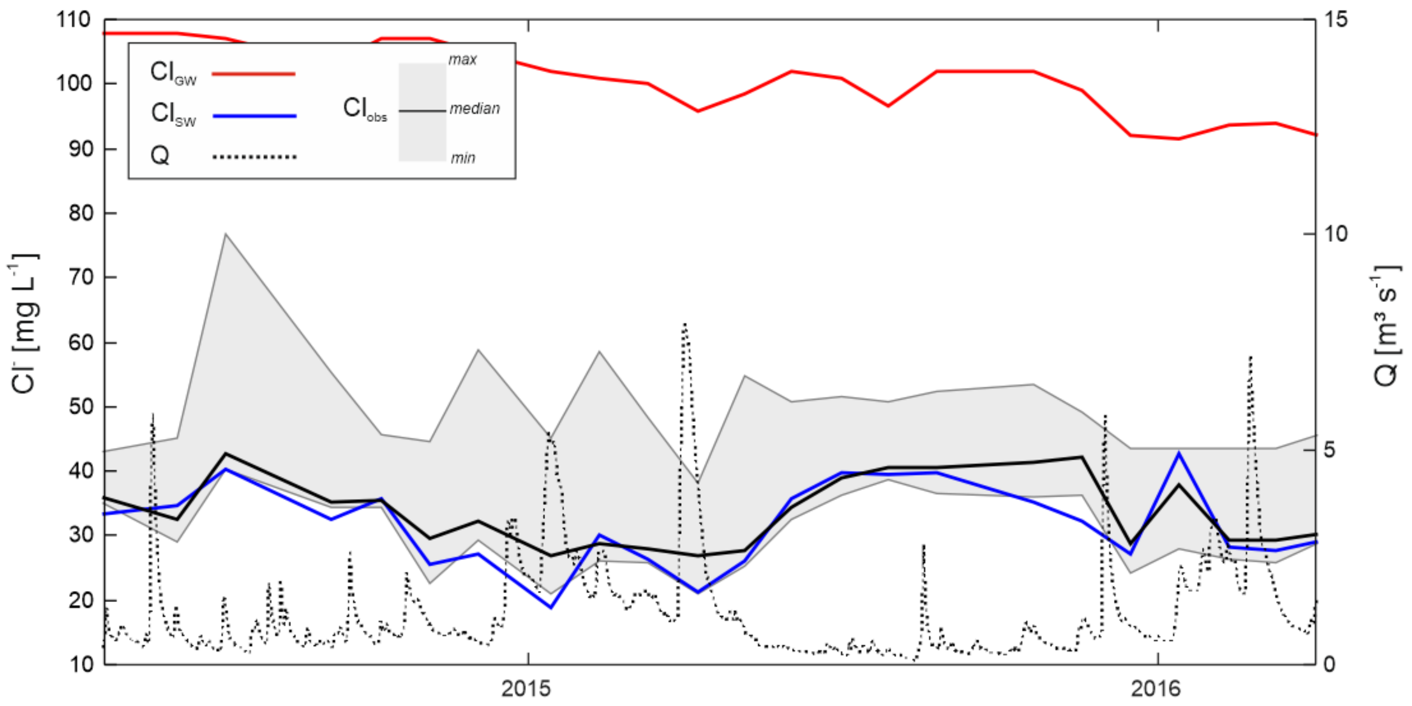
$$d = 1 - \left[\frac{\sqrt{\left(1/w - f_1\right)^2 + \left(1/w - f_2\right)^2 + \ldots + \left(1/w - f_w\right)^2}}{\left(\sqrt{2} \times \sqrt{w}/w\right)} \right]$$

or

$$d = 1 - \left[\frac{\sqrt{\left(1/2 - f_{sw}\right)^2 + \left(1/2 - (f_{GW} + f_{FD})\right)^2}}{\left(\sqrt{2}/2\right)} \right]$$

Measured Cl^- concentrations for HMC validation





Measured Cl^- concentrations from groundwater *end-member* (Cl_{GW}), surface water *end-member* (Cl_{SW}), and observation wells (Cl_{obs}). Q is the stream discharge.

Flow paths, velocities and mixing degrees

Particles released at the streambed (≈300) and floodplain (1,000)

Release locations: