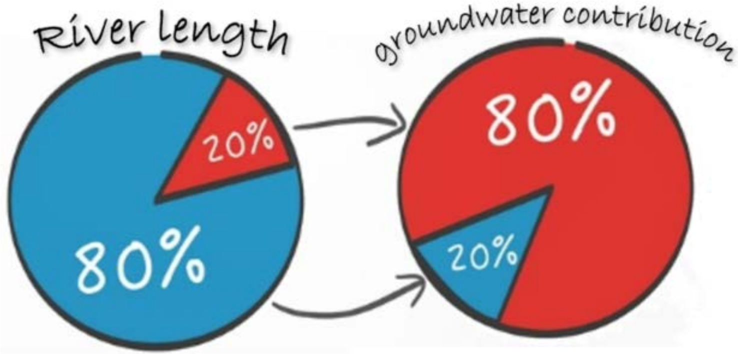
The effect of stream-groundwater exchange on stream water source composition



Zhi-Yuan Zhang, Christian Schmidt, Jan Fleckenstein

HDG Seminar, April 9, 2021

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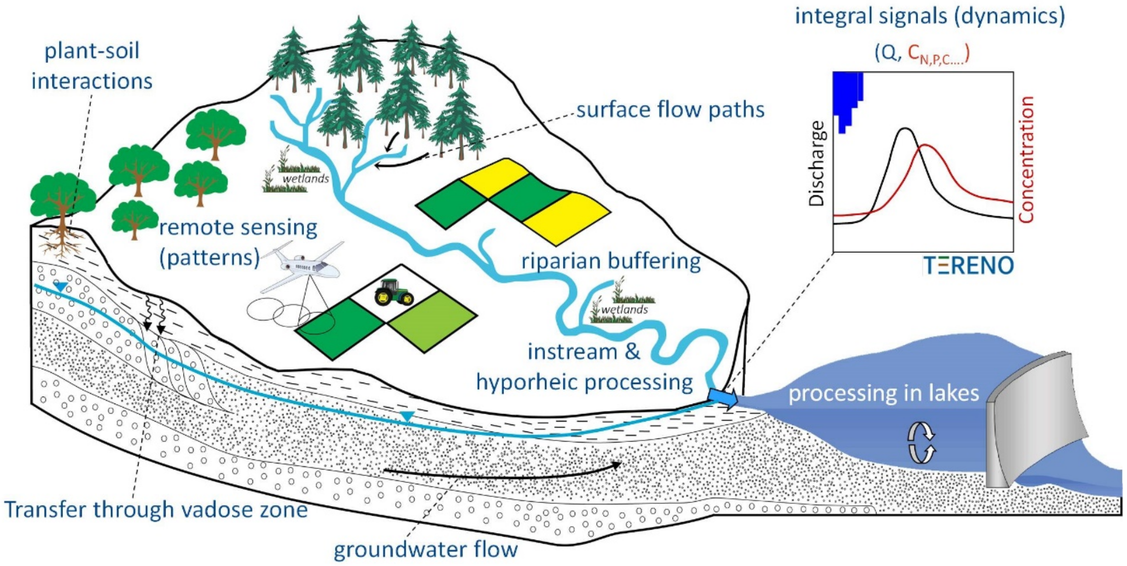
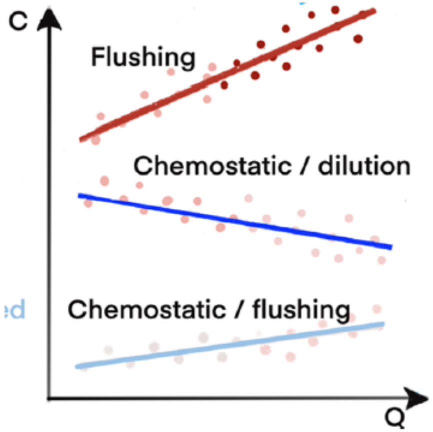
1 Introduction & Questions



(Source J. Fleckenstein)



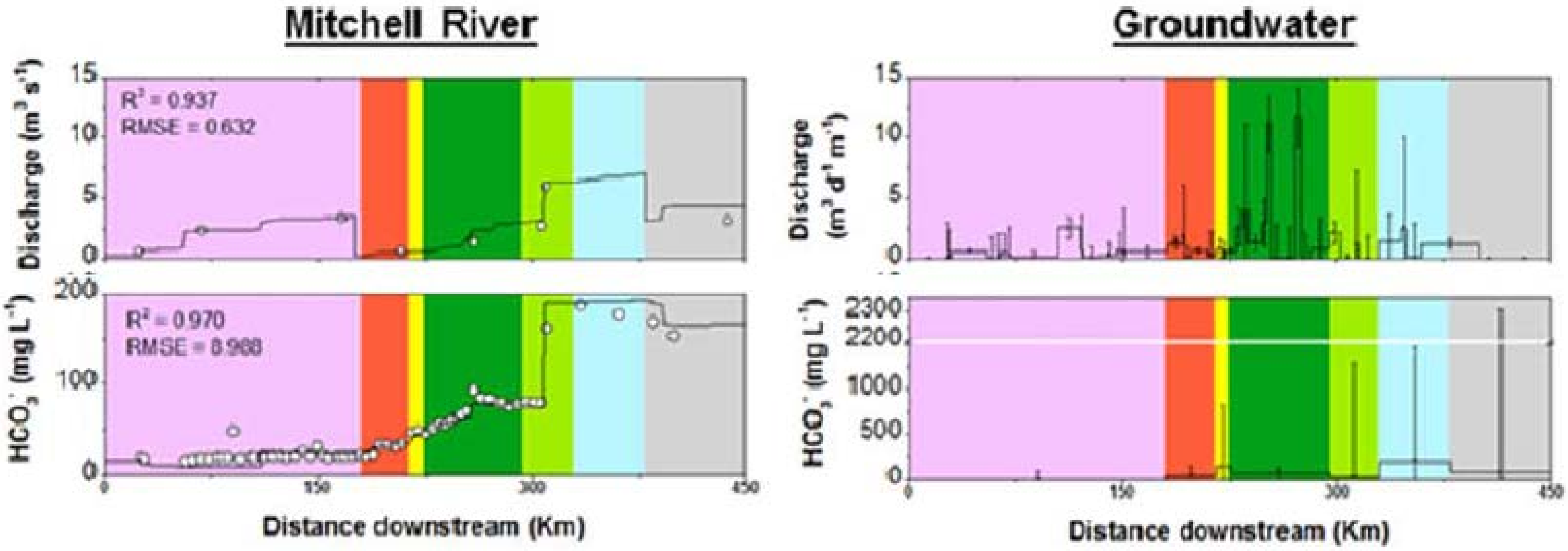
(Zhi & Li, 2020)

Solute and hydrologic signals ← transport processes in the stream network

(1) Stream gains → stream water source (composition)

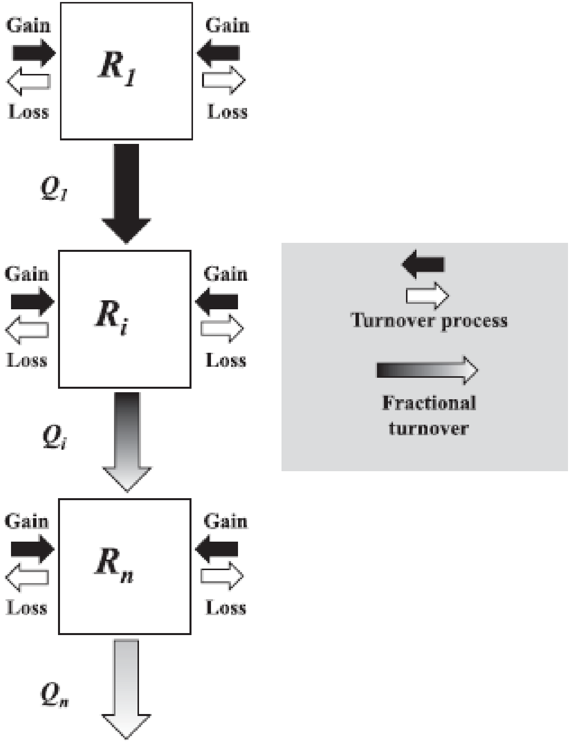
Q_{gain}: heterogeneous

C_{gain}: heterogeneous

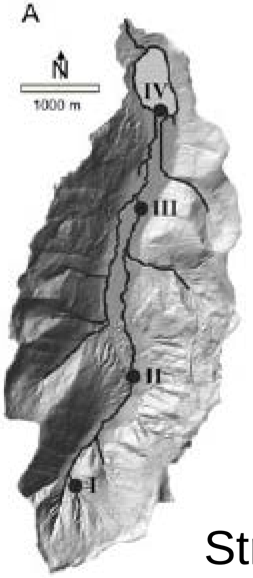


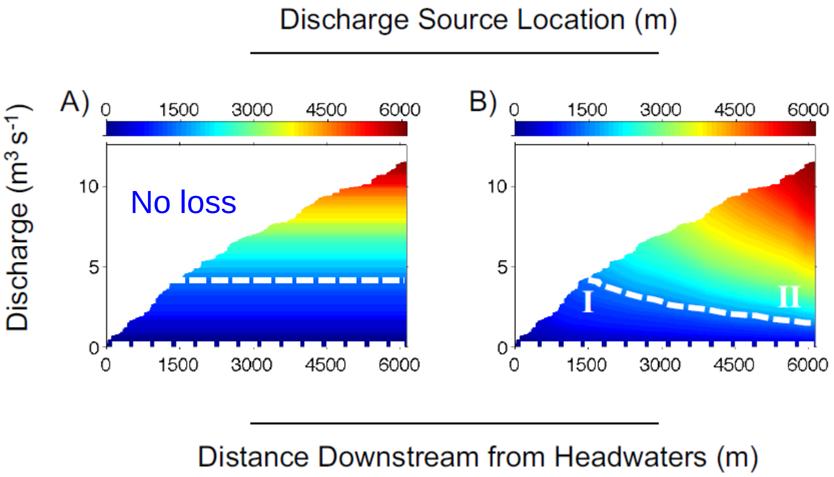
(Batlle-Aguilar et al., 2013)

(2) Stream losses → stream water source composition



Hydrologic turnover
(Covino et al., 2011)

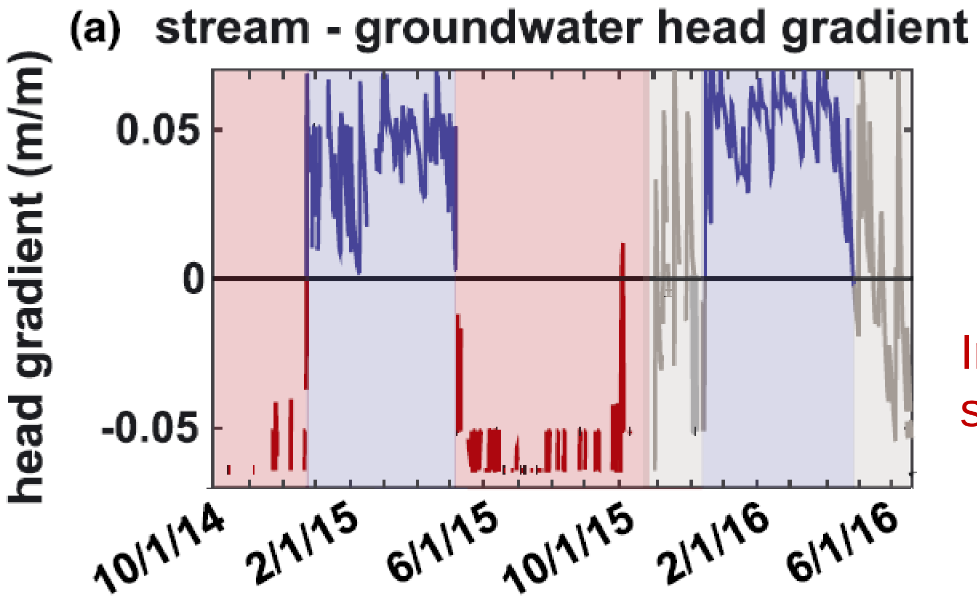




Stream water source composition (Mallard et al., 2011)

Solute load contribution ∝ flow contribution ?

(3) Stream gains ←→ stream losses



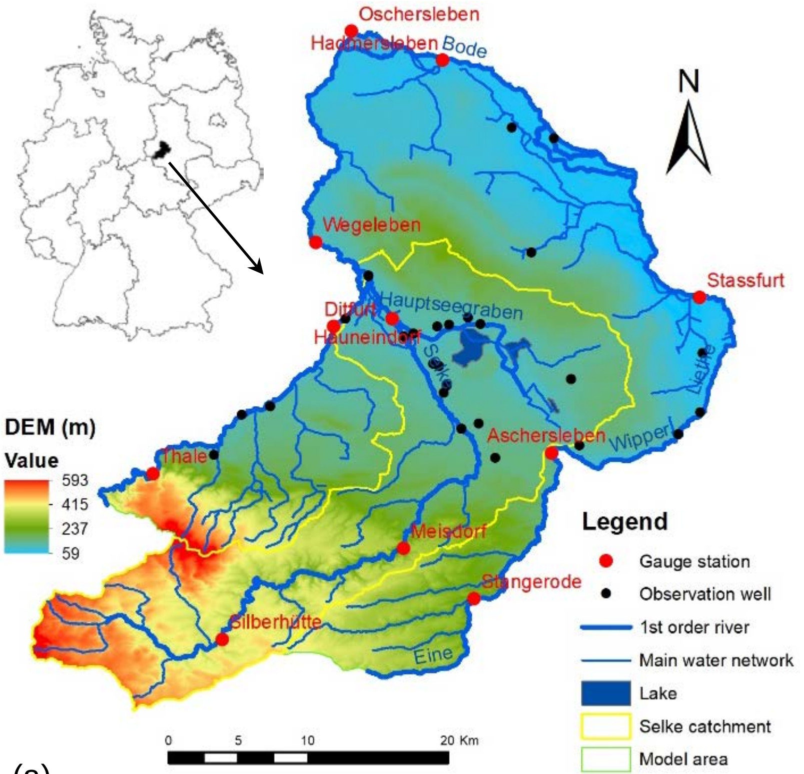
Influence of hydrologic conditions on stream water source composition?

Time series of stream–groundwater head gradient

(Zimmer et al., 2017. HP)

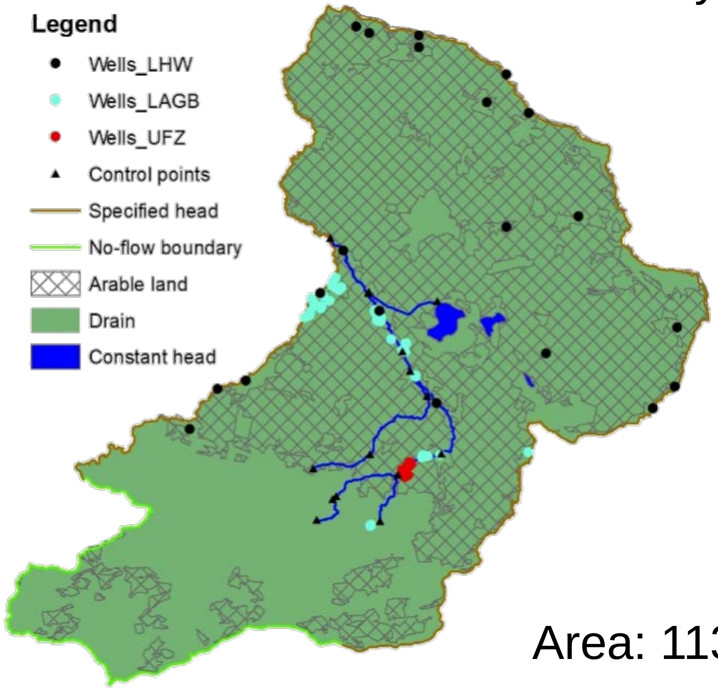
2 Method & Model

Steady-state



(a)

Study area



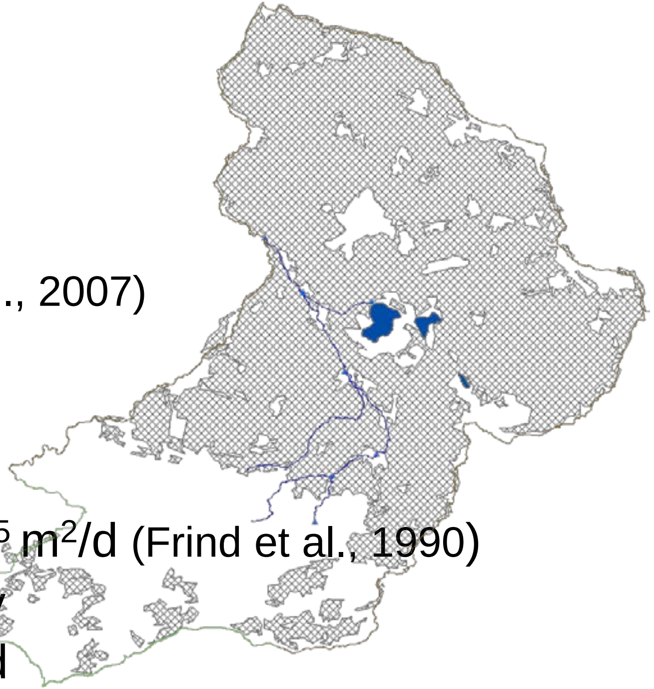
Area: 1130 km^2

River: 30 km

(b)

Boundary conditions

Solute transport simulation



Simulating nitrate transport with MT3D (Almasri et al., 2007)

Advection: Velocity from flow model

Dispersion: Longitudinal dispersivity: 50 m,

Transerve/vertical ratio: 0.1

Diffusion coefficient for nitrate: 5×10^{-5} m^2/d (Frind et al., 1990)

Chemical reaction: Denitrification → first-order decay

First-order decay coefficient: 0.001 /d

$\lambda = \frac{0.693}{\tau_{1/2}}$, τ: 1 ~ 2.3 year, λ: 0.000825 ~ 0.0019 /d.

Source: Uniform Nitrate loading: 5 kg/ha/yr. (Jiang et al., 2019)

Soil nitrogen transformation such as plant uptake is not considered.

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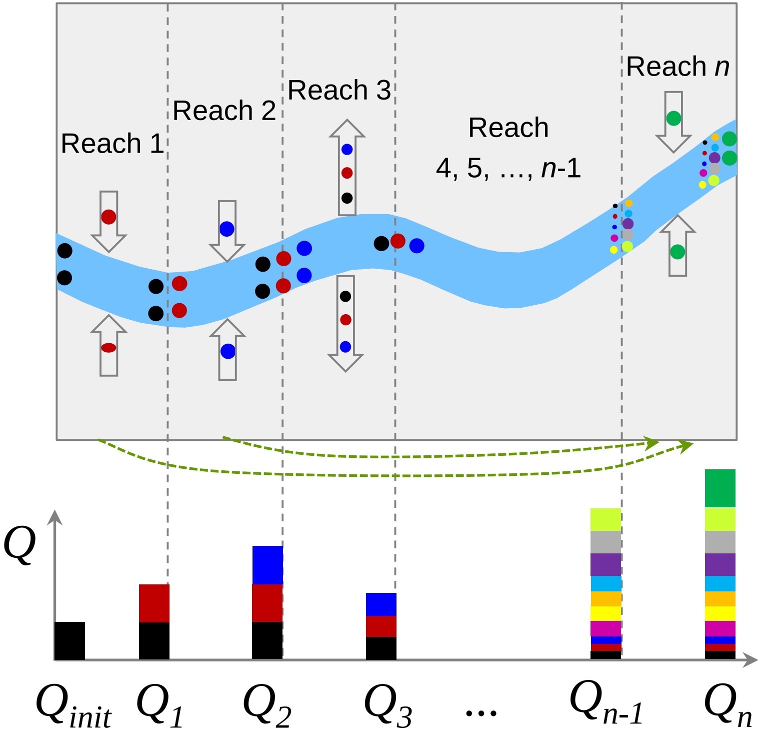
Calculation of source composition



Sequential stream-groundwater exchange

$$R_i = \begin{cases} 1, & if\ Q_{gain,i} \geq 0 \\ \frac{Q_i}{Q_{i-1}}, & if\ Q_{gain,i} < 0 \end{cases}, i = 1, 2, 3...$$

$$Q_{i,j} = \begin{cases} 0, & if\ Q_{gain,j} \leq 0 \\ Q_{gain,j} \times \prod_{k=j}^{i} R_k, & if\ Q_{gain,j} > 0 \end{cases}, i = 1, 2, 3..., j = 1, 2, 3, ..., i$$

$$LC_{i,j} = \begin{cases} 0, & if\ Q_{gain,j} \leq 0 \\ C_{gain,j} \times Q_{gain,j} \times \prod_{k=j}^{i} R_k, & if\ Q_{gain,j} > 0 \end{cases}, i = 1, 2, 3..., j = 1, 2, 3, ..., i$$

$$C_{s,i} = \frac{L_{s,i}}{Q_{s,i}} = \frac{\sum_{k=0}^{i} LC_{i,k}}{\sum^{i} Q_{i,k}}, i = 1, 2, 3...$$

R_i : remaining fraction ;

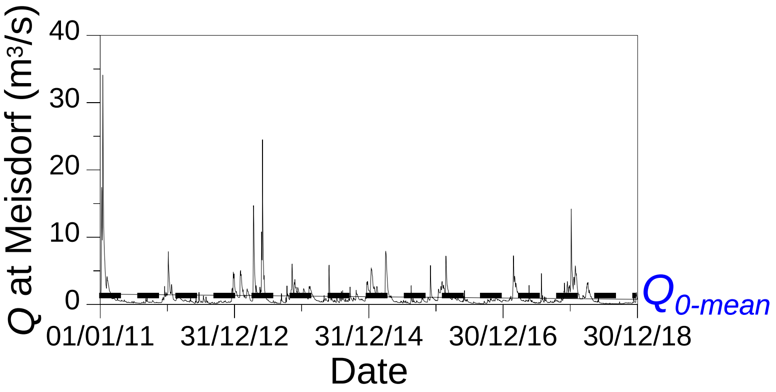
$Q_{gain,I}$ & $C_{gain,j}$: stream gains across reach *i* and corresponding conc. ;

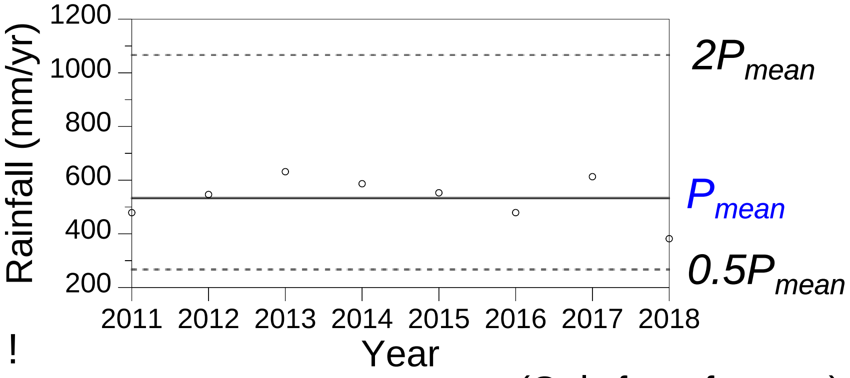
$Q_{i,j}$ & $LC_{i,j}$: flow and load contribution from reach *j* to *i*.

$Q_{s,I}$ & $L_{s,i}$ & $C_{s,}$: discharge, solute load and conc. in stream reach *i*;

Scenarios

Scenario	Q_0 (m^3/s)	P/P_{mean}
S1	0.087	0.5
S2	1.15	
S3	2.3	
S4	0.087	1
S5 (baseline)	1.15	
S6	2.3	
S7	0.087	2
S8	1.15	
S9	2.3	
S10	34.1	1

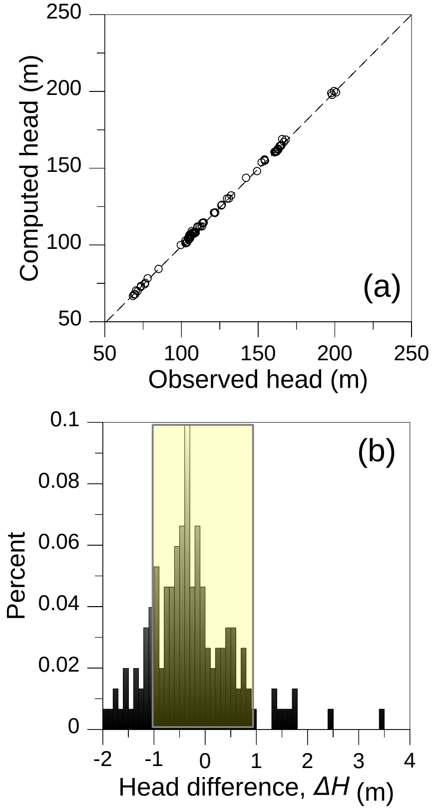


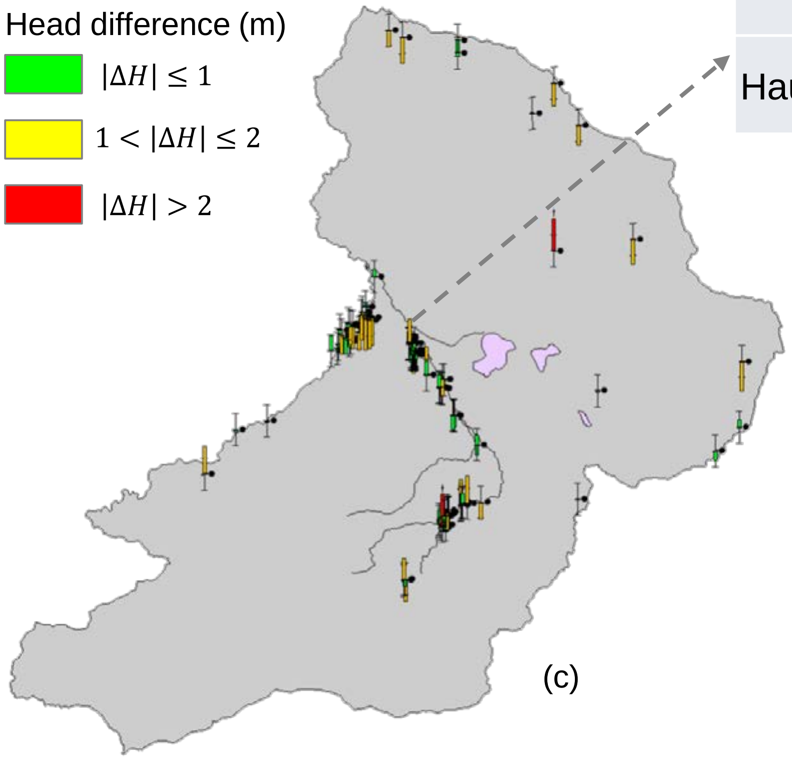


All simulations are steady-state !

(Only for reference)

2.8 Model calibration



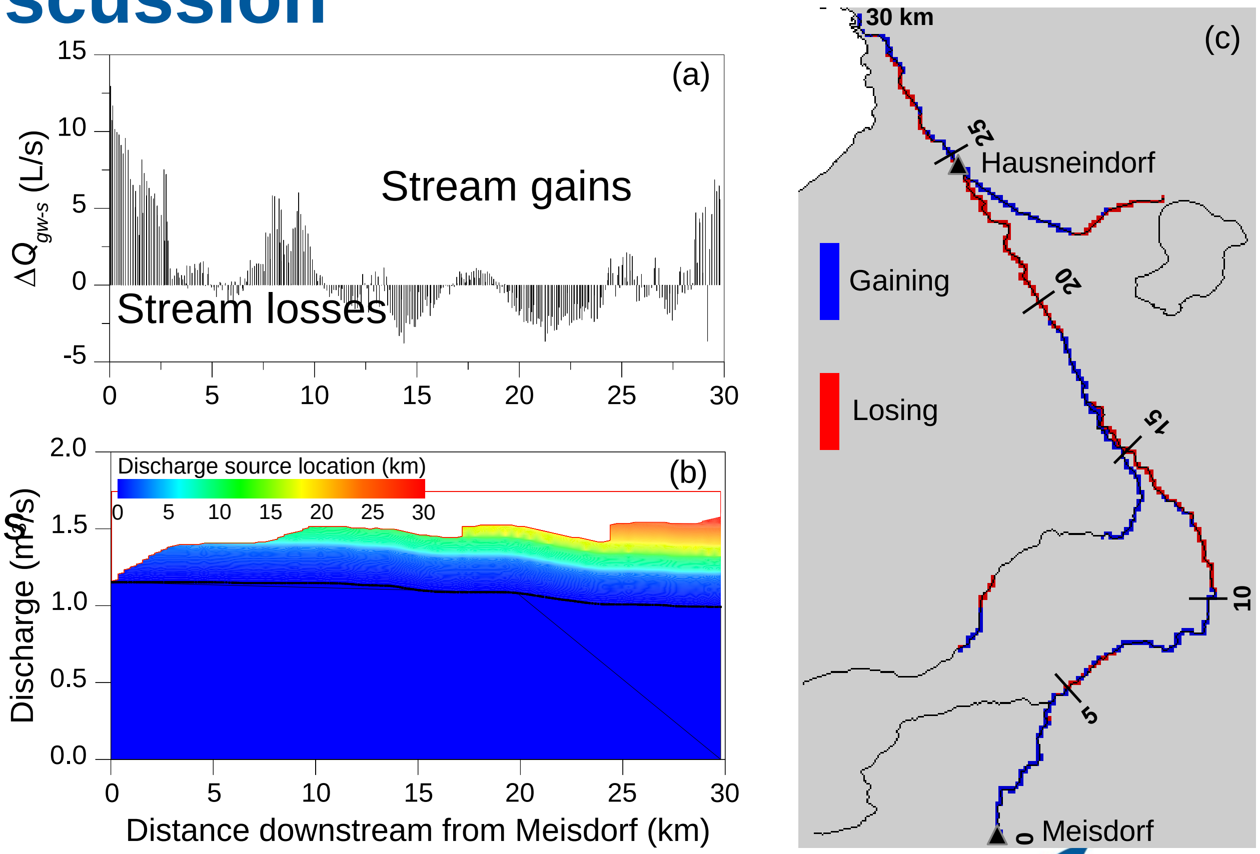


	Q_{obs} (m³/s)	Q_{sim} (m³/s)
Hausneindorf	1.543	1.531

3 Results & discussion

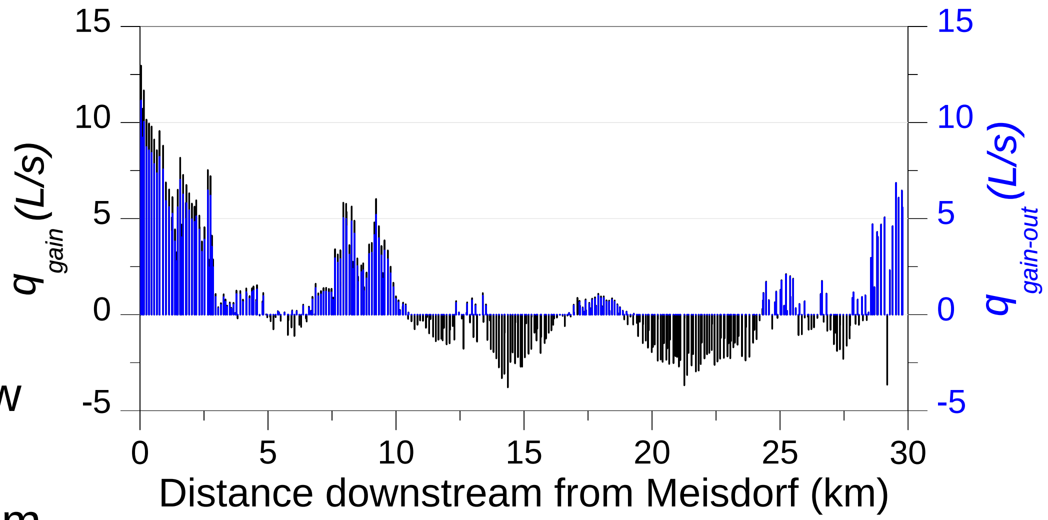
3.1 Baseline case

Sequential stream gains and stream losses



Stream-groundwater exchange and source composition

Initial stream gains vs. Remaining fraction



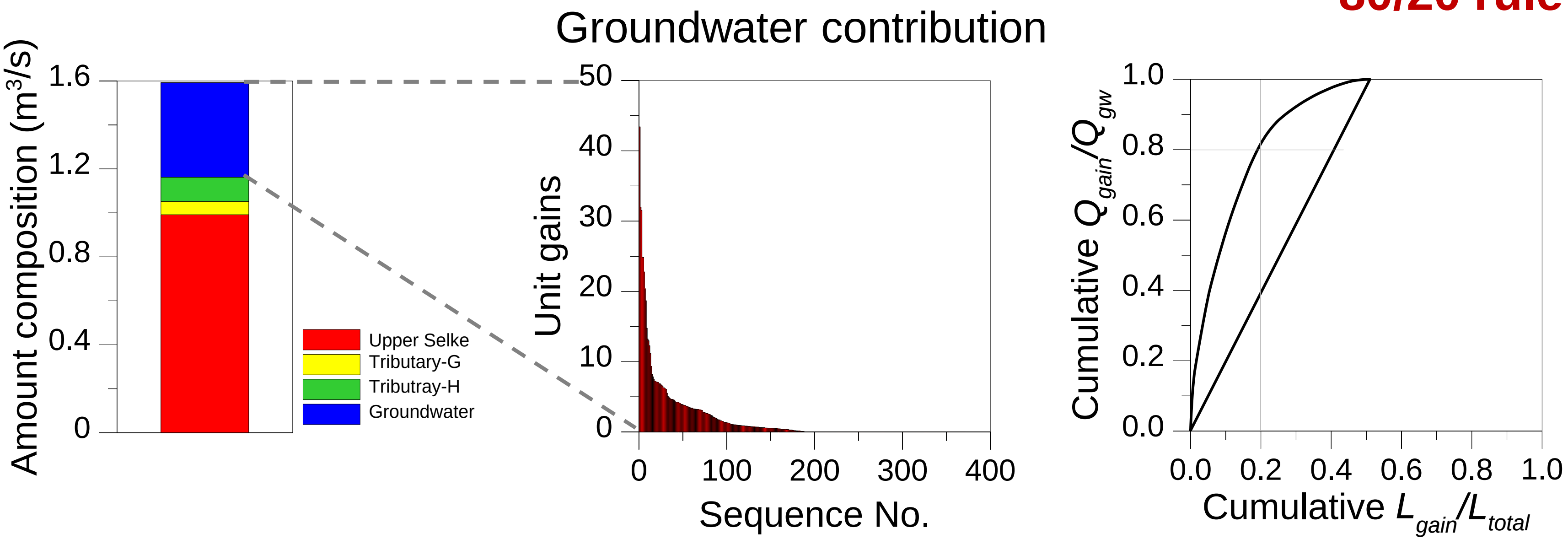
q_{gain}: water initially gained from gw

$q_{gain-out}$: water contributed to stream

water at the outlet

Source composition of stream water at the outlet

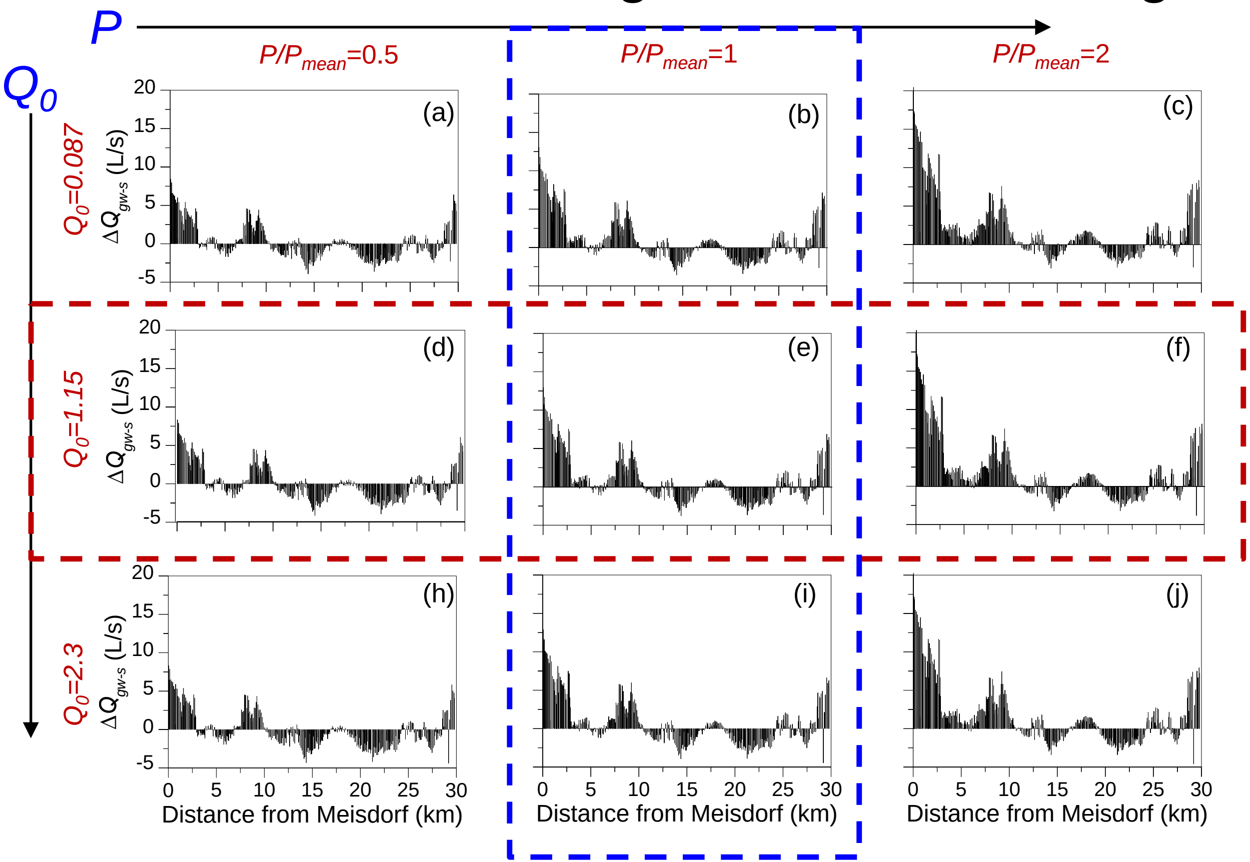
80/20 rule !



$$\text{Unit gains} = \frac{stream\ gains}{reach\ length}$$

3.2 Effect of hydrologic conditions on stream-groundwater exchange

As P ↑ or Q ↓,
Gaining velocity ↑
Gaining length ↑



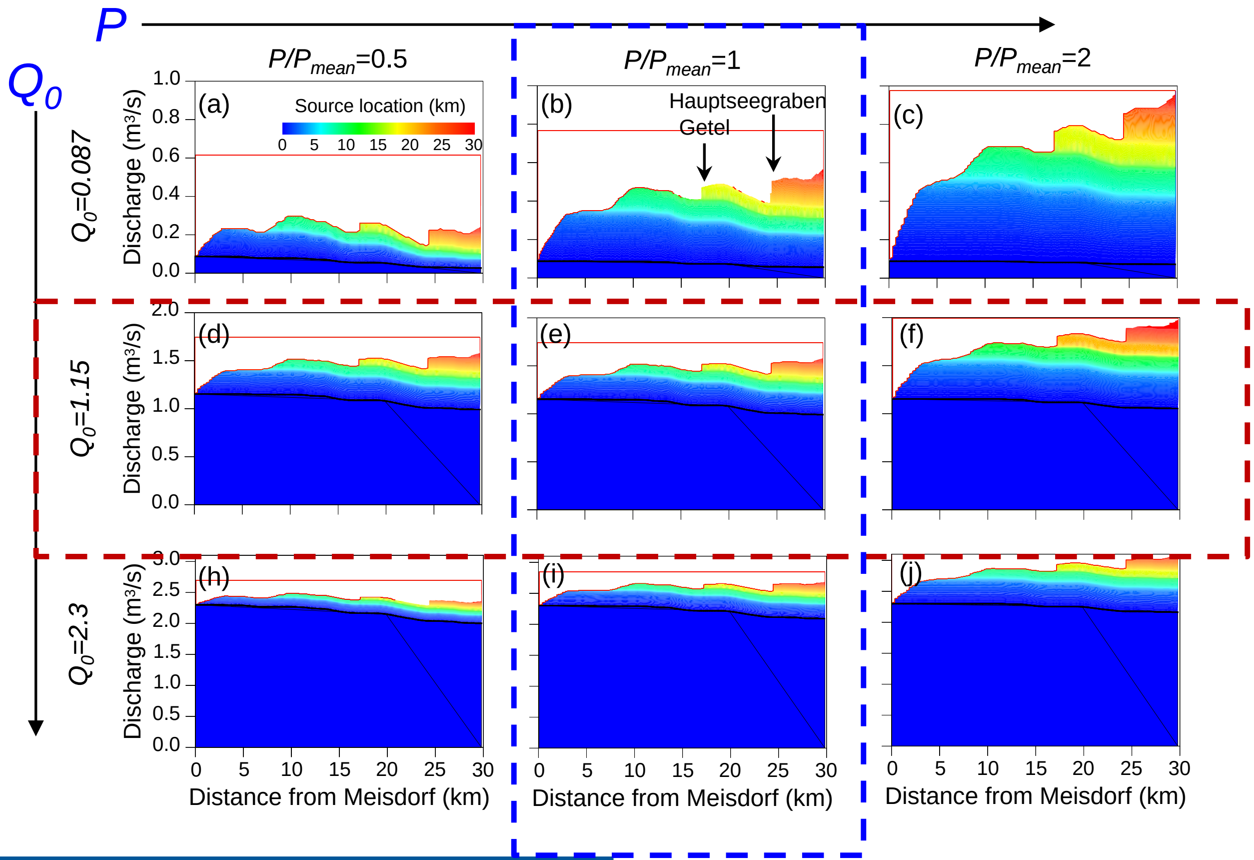
3.3 Effect of hydrologic conditions on stream source composition

As P ↑ or Q ↓

Hydrologic turnover ↑

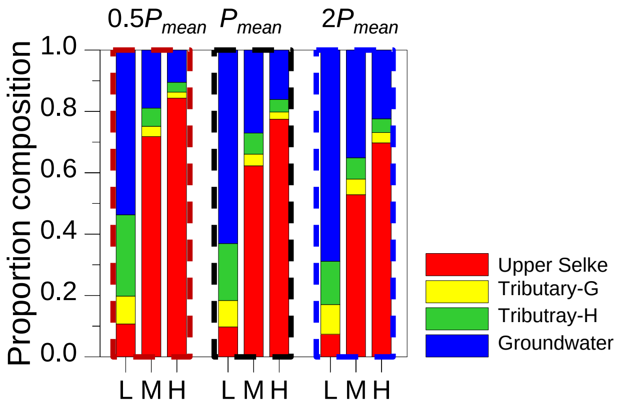
(Upstream contribution ↓

Downstream contribution ↑)

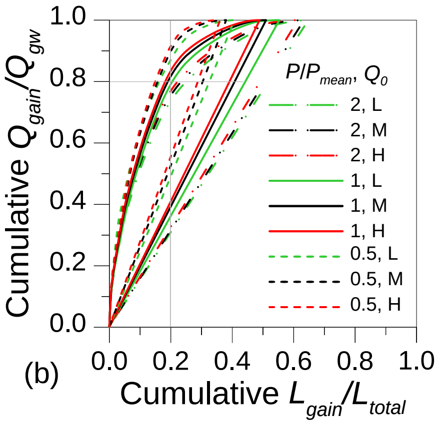


3.4 Source composition of stream water at the outlet

80/20 rule !



(a)



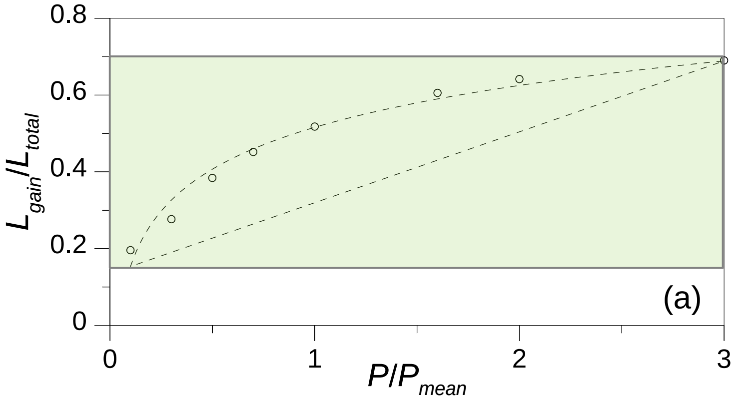
(b)

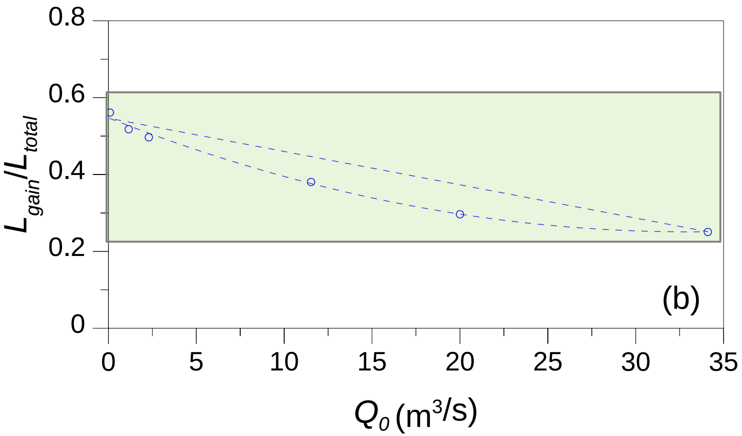
As P ↑ or Q ↓,

Groundwater contribution ↑

3.5 Three types of reaches

Monotonous change

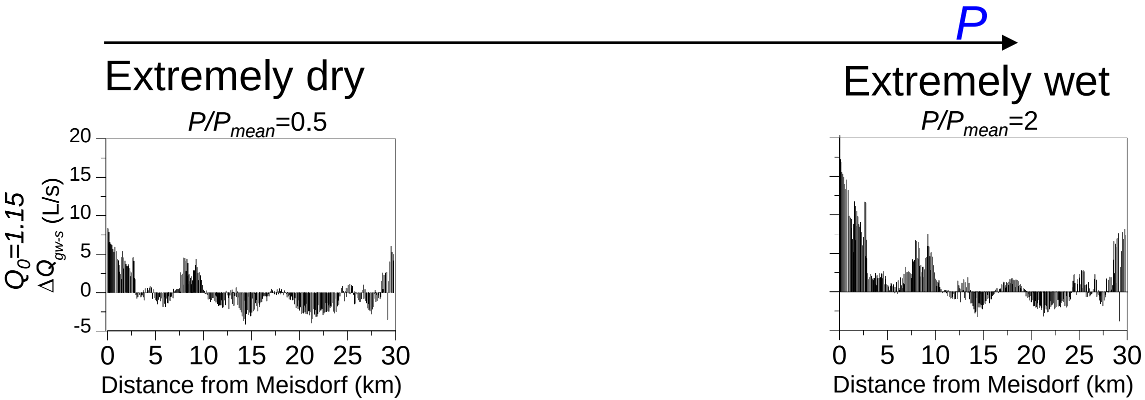


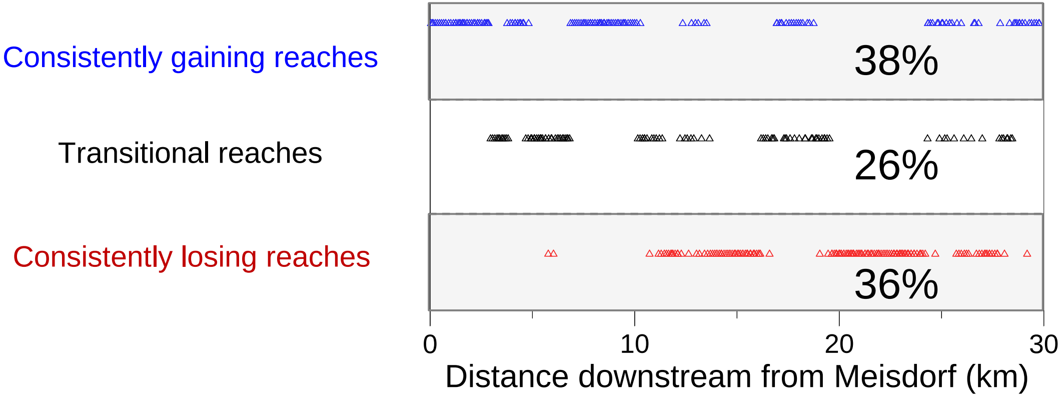


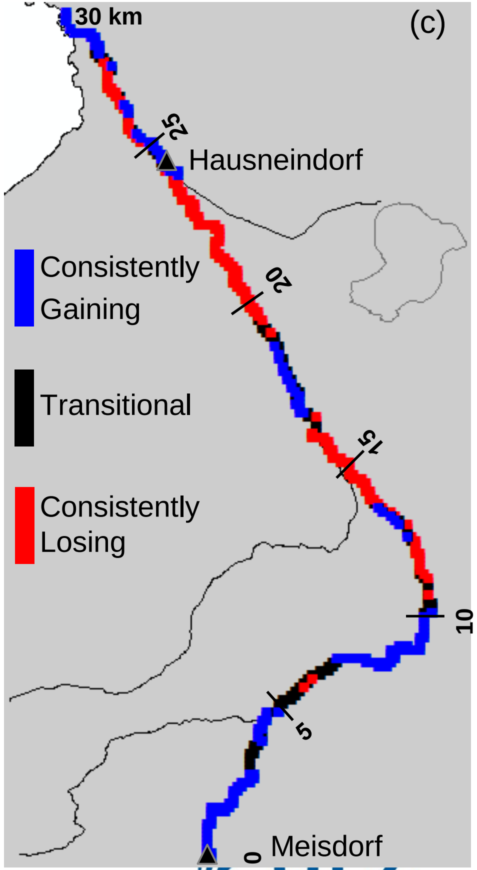
Precipitation vs. L_{gain}

Streamflow vs. L_{gain}

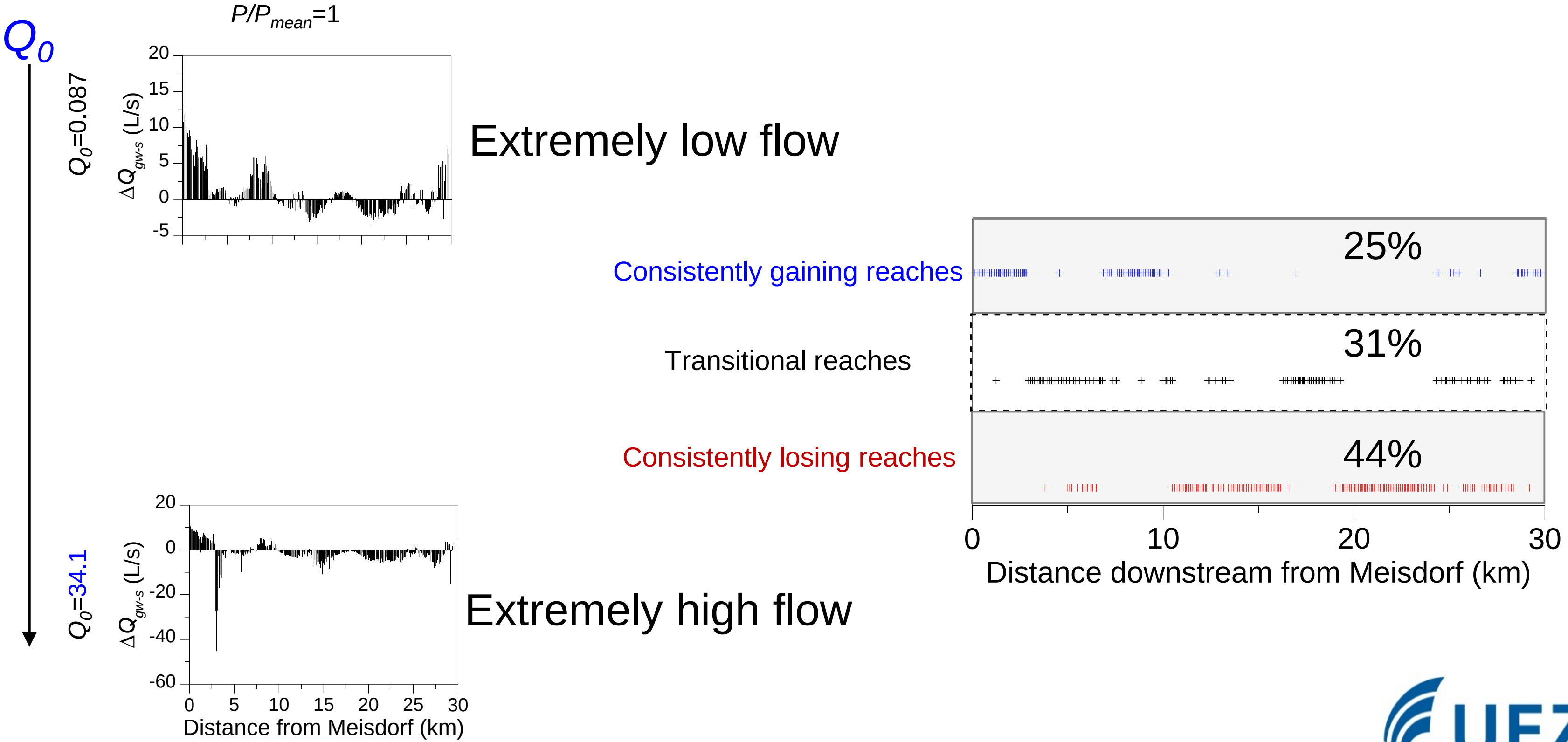
3.5 Three types of reaches







3.5 Three types of reaches



Implication of three types of reaches on stream management

Consistently gaining reaches (CGR)

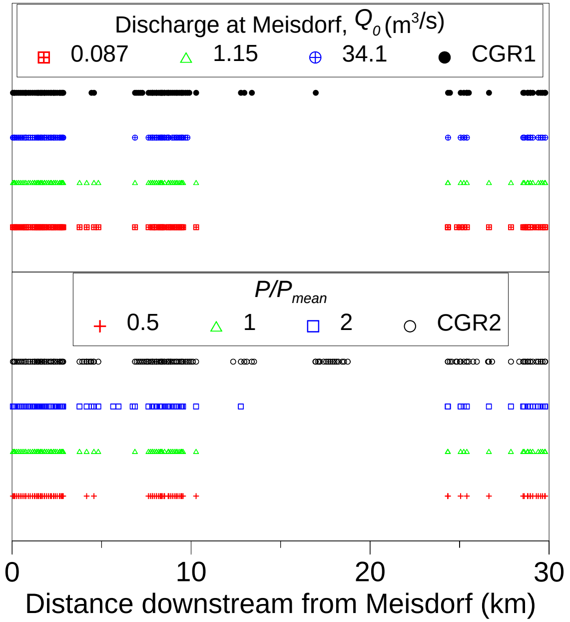
→ stream water source

Transitional reaches

→ biogeochemical reaction

Consistently losing reaches

→ groundwater



Top 20% reaches

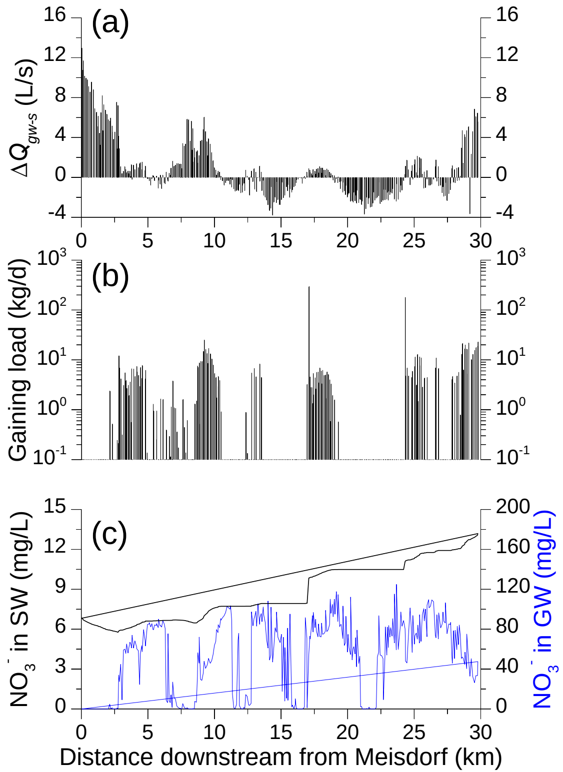
Range:

Top 20% reaches

< CGR

≤ Gaining reaches

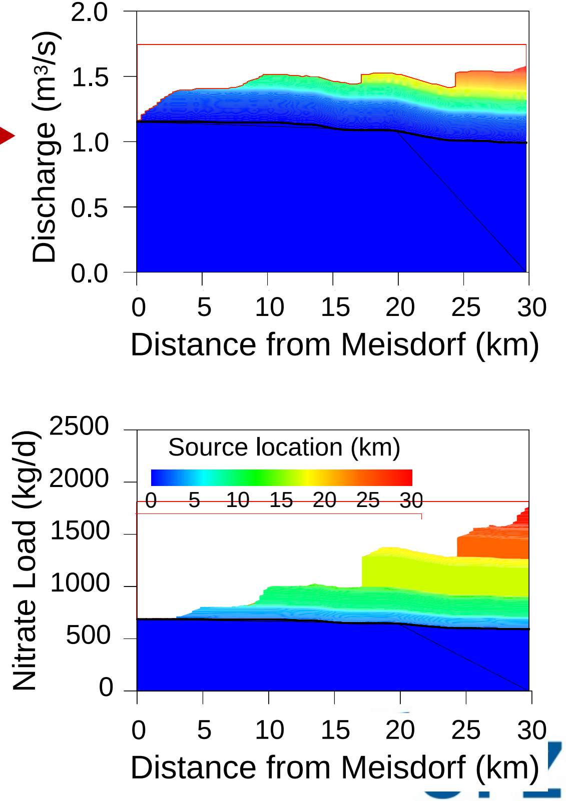
3.6 Source composition of nitrate load in stream water



Water exchange

Nitrate exchange

Nitrate Conc.
In SW vs. GW



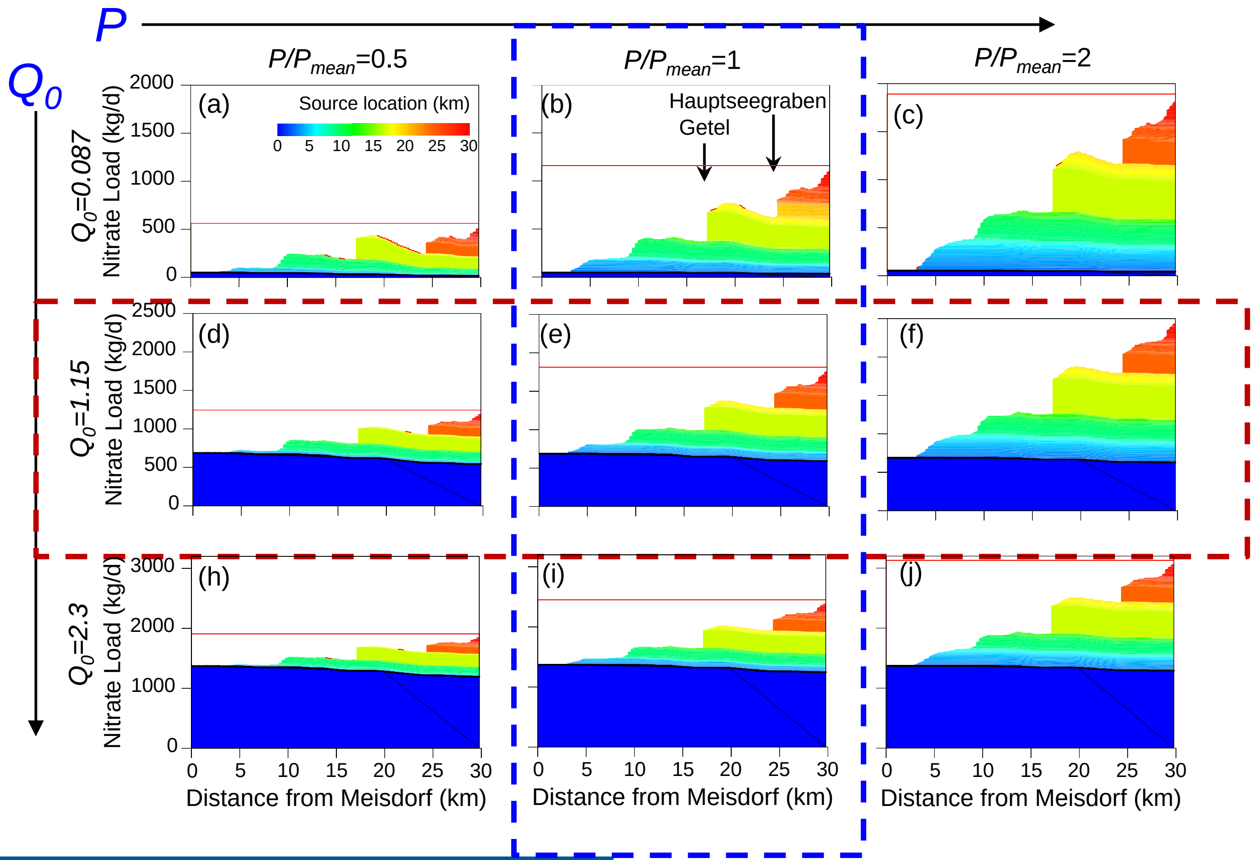
3.7 Effect of hydrologic conditions on source composition of load

As P ↑ or Q ↓

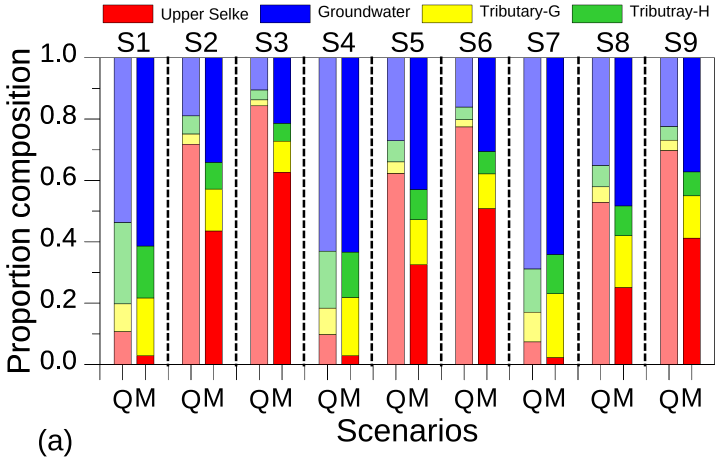
Hydrologic turnover ↑

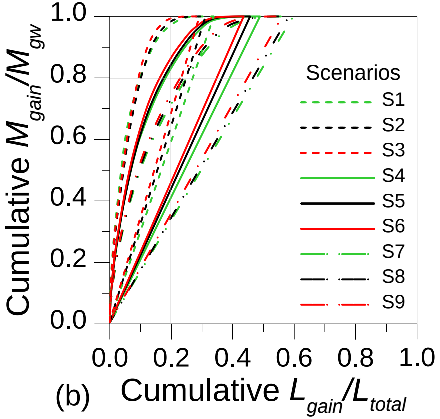
(Upstream contribution ↓

Downstream contribution ↑)



3.8 Source composition of nitrate load in outlet's water





Scenario	Q_0 (m^3/s)	P/P_{mean}
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S2	1.15	
S3	2.3	
S4	0.087	1
S5 (baseline)	1.15	
S6	2.3	
S7	0.087	2
S8	1.15	
S9	2.3	

(1) Flow contribution ≠ solute load contribution

(2) 80/20 rule

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4 Limitations

Not considered:

Transient flow conditions;

Vadose zone ;

Hyporheic exchange ;

Complex nitrate reaction.

5 Take home messages

1. Both stream gains and stream losses matter in stream water composition;

2. Groundwater flow contribution ≠ solute load contribution;

3. Most of the groundwater contributions to outlet's stream water

   are generated over only a few reaches.

Welcome for comments and questions!

References

Batlle-Aguilar, J., Harrington, G. A., Leblanc, M., Welch, C., & Cook, P. G. (2014). Chemistry of groundwater discharge inferred from longitudinal river sampling. Water Resources Research, 50(2), 1550-1568.

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