Asymmetric quantification of stream-groundwater interaction based on Stream Aquifer Flow Exchange (SAFE) method

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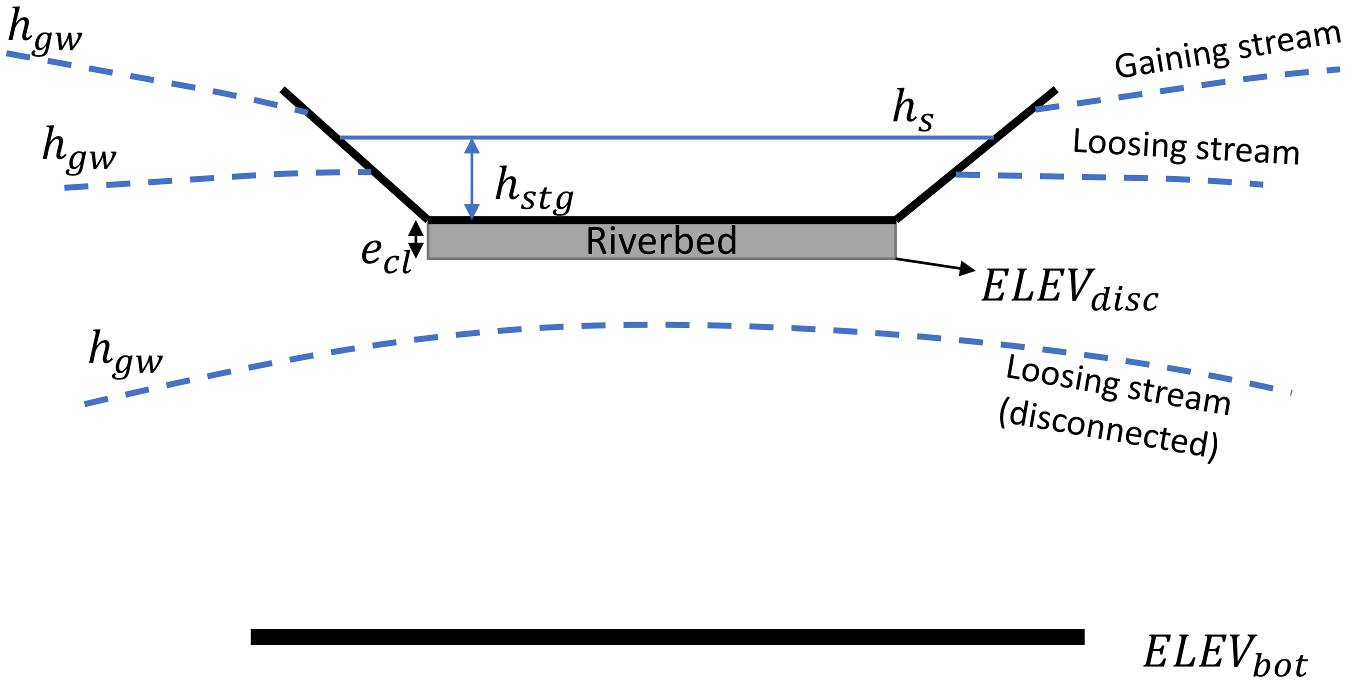
Overview

- Stream Aquifer Flow Exchange (SAFE)
- Improvements on the disconnection criterion
- Asymmetric quantification of stream-groundwater interaction
- Examples
  - Test case
  - C2VSim
- Conclusions

Traditional approach (RP)

$$Q_s = \frac{K_{cl}}{e_{cl}} LW_{per}(h_s - h_{gw})$$

- Issues with the traditional approach:
  - SW-GW predominately vertical process
  - Riverbed conductance K_{cl} has no physical meaning. Depends on hydrology conditions which may change over time
  - Wetted perimeter is constant during the simulation
  - Disconnection occurs at the bottom of the riverbed

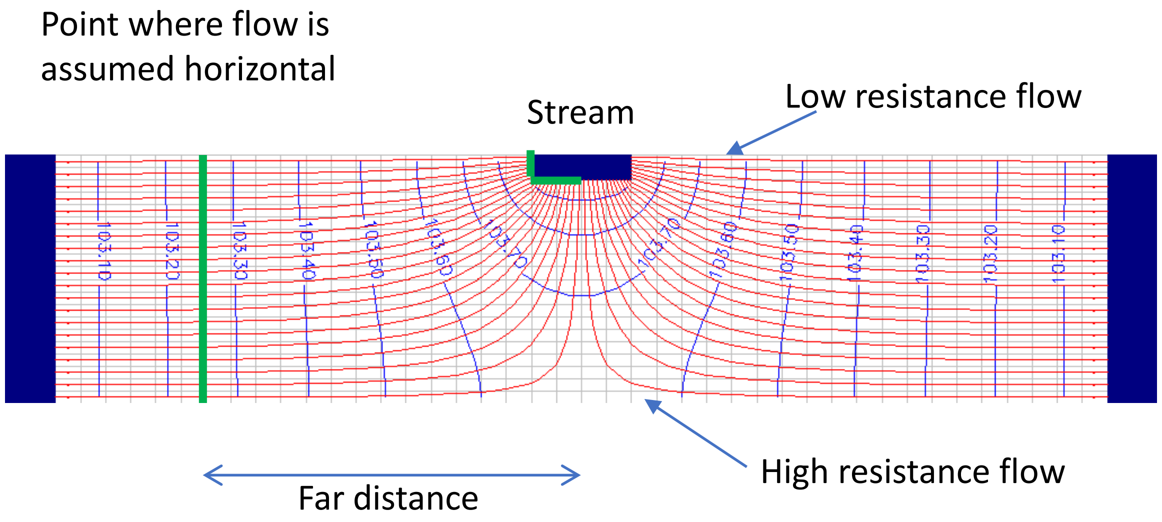


*We denote as RP the current implementation in Modflow, IWFM, GSFLOW and others and not the Modflow RIV package

Stream Aquifer Flow Exchange (SAFE)

$$Q_s = 2L\,\Gamma\,K_H\left(h_s - h_{gw}\right)$$

- Calculates stream-aquifer exchange as a function of the flow resistance between the stream and a point at the aquifer where the flow can be assumed horizontal
- The resistance is not uniform!
- The core of SAFE is the dimensionless coefficient Γ which represents the integral of resistances between the two crossections



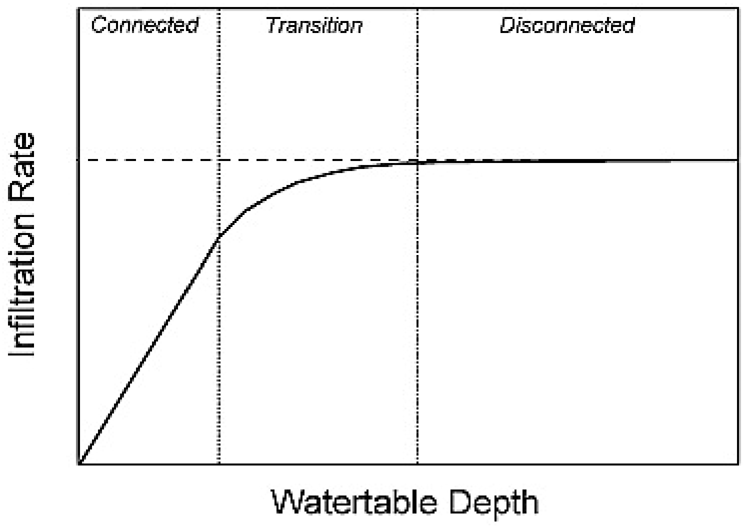
L : River segment length
K_H Horizontal hydraulic conductivity
Γ : SAFE coefficient

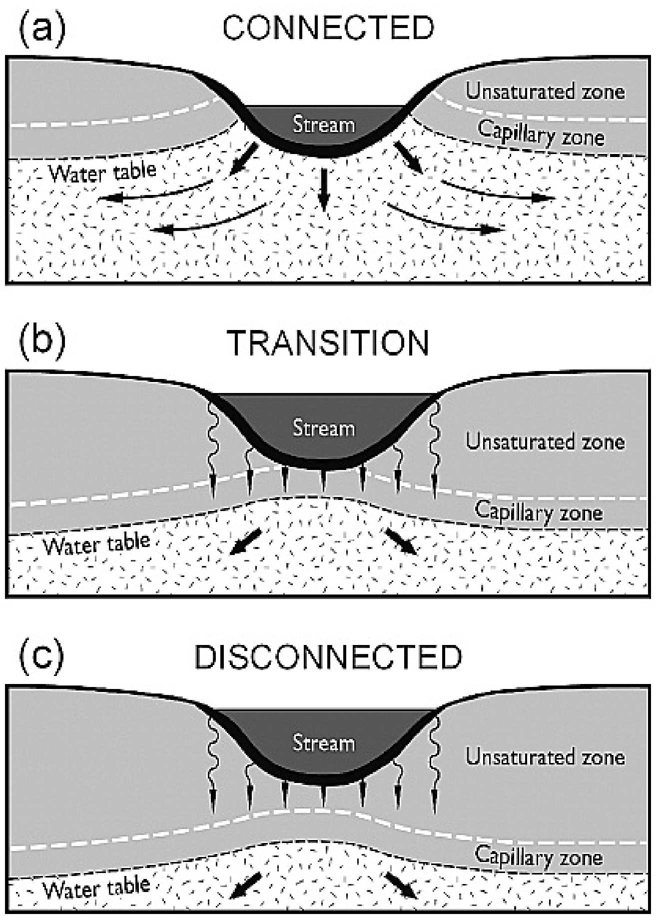
Traditional disconnection criterion

- In practice the head difference is calculated as

$$h_{diff} = h_s - \max(h_{gw}, Elev_{rbed})$$

- The RP approach assumes the disconnection occurs at the bottom of the riverbed and ignores the transition zone due to mounding
- It is known that this approach underestimate the infiltration rate





The Figures are from: Brunner, P., Cook, P. G., & Simmons, C. T. (2009). Hydrogeologic controls on disconnection between surface water and groundwater. Water Resources Research, 45(1). https://doi.org/10.1029/2008WR006953

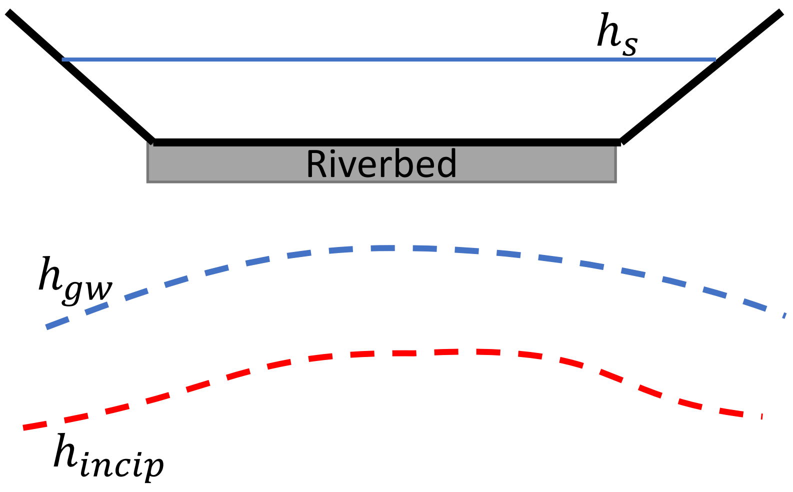
SAFE disconnection criterion

- The disconnection depends on the incipient desaturation

$$h_{incip} = h_s - \frac{W_{per}}{2K_H\Gamma} K_{cl} \frac{h_{stg} + e_{cl} + h_{ce}}{e_{cl}}$$

$$h_{diff} = h_s - \max(h_{gw}, h_{incip})$$

- river width
- thickness of the aquifer
- thickness of the clogging layer
- conductivities of the clogging layer and of the aquifer
- entry pressure of the aquifer (drainage)
- ponded depth over the riverbed and aquifer head at some distance from the riverbank



Stream is still connected to aquifer even if h_{gw} is below riverbed because $h_{gw} > h_{incip}$

h_s : Stream head
W_{per} : Wetted perimeter
K_H : Hydraulic conductivity
Γ : SAFE coefficient
K_{cl}: Riverbed conductivity
e_{cl} : Riverbed thickness
h_{stg}: Stream stage
h_{ce} : drainage entry pressure

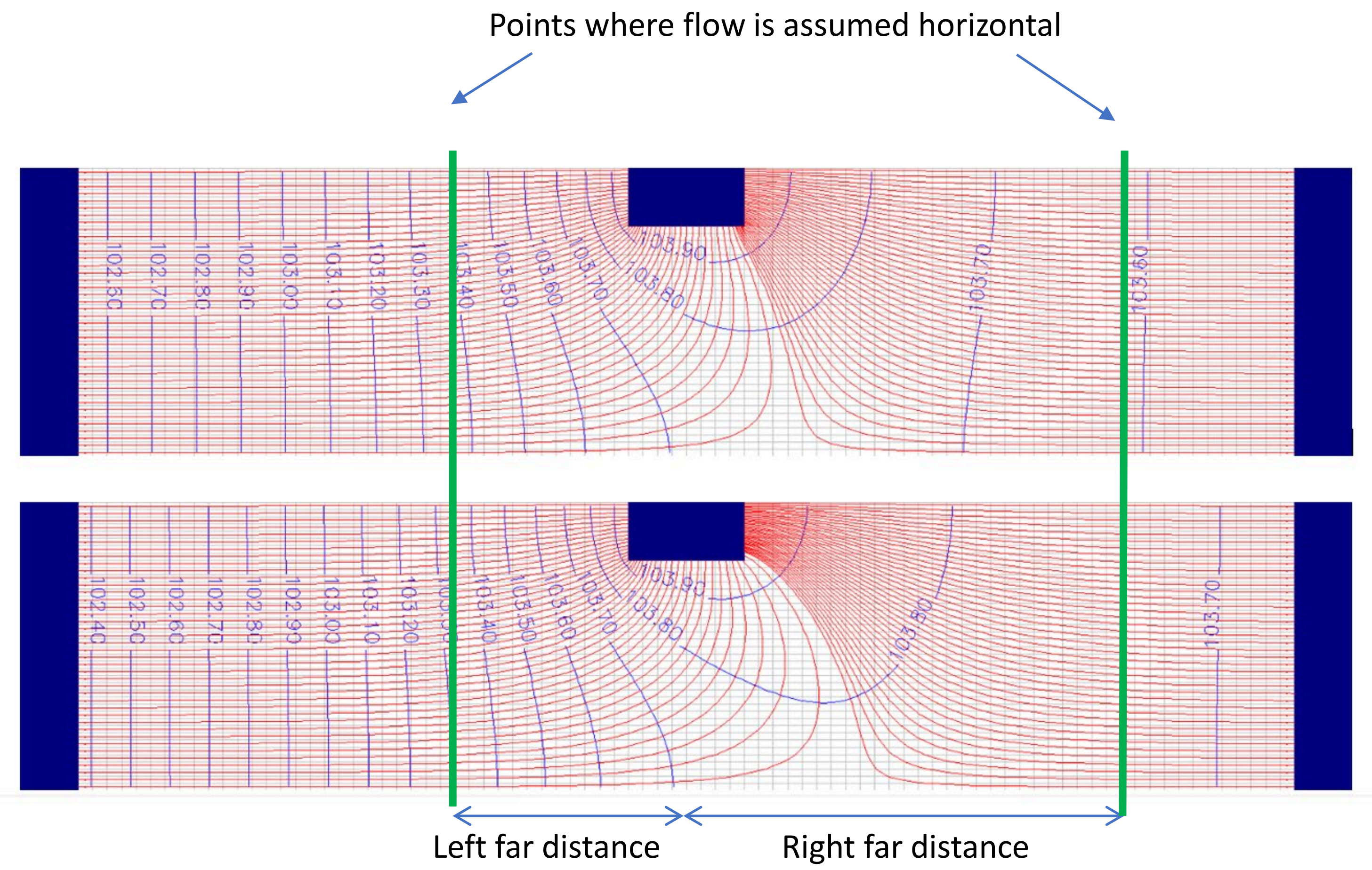
Asymmetric quantification of stream-aquifer flow exchange

- SAFE allows the calculation of a different flow resistance on the left and the right

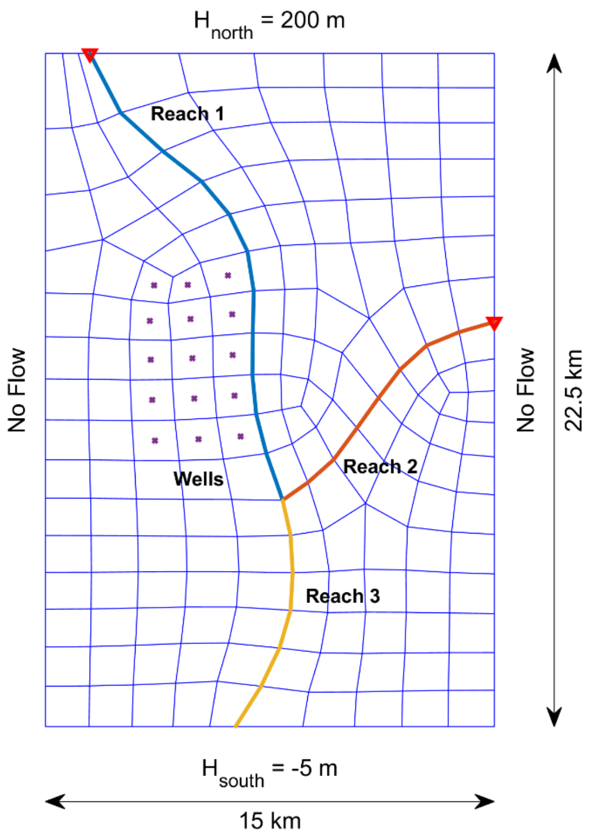
$$Q_s^L = L\Gamma^L K_H(h_s - h_{gw}^L)$$

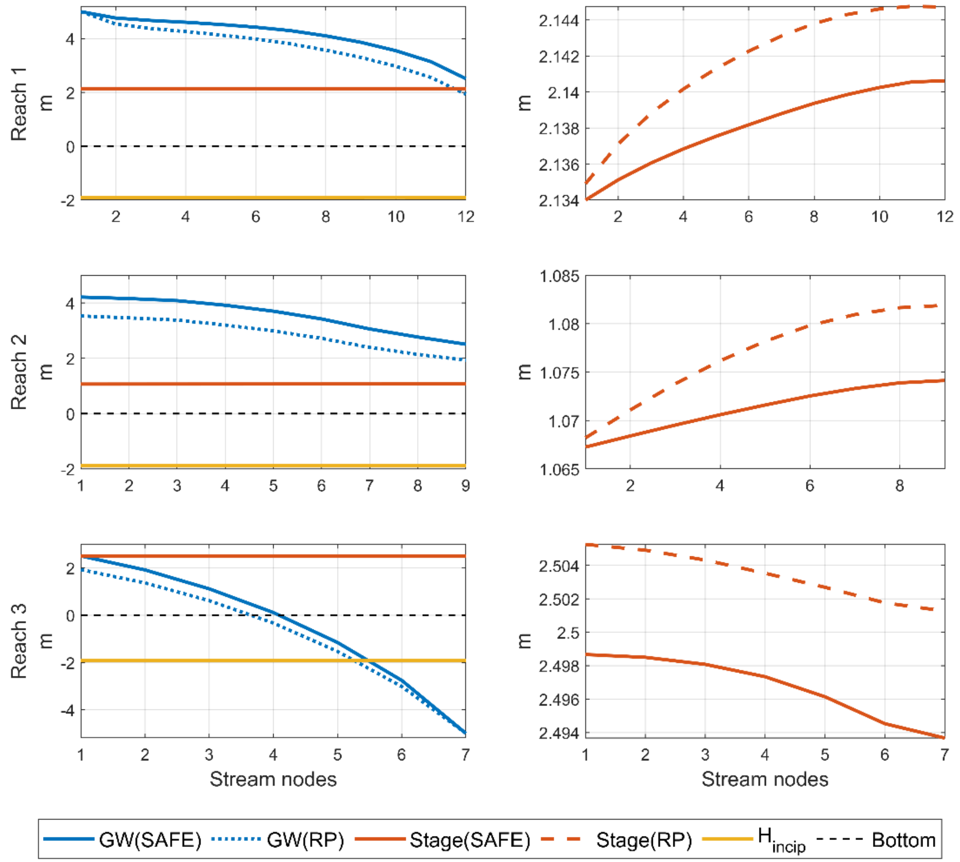
$$Q_s^R = L\Gamma^R K_H(h_s - h_{gw}^R)$$

- h_{gw}^L, h_{gw}^R can be calculated
  - By the finite element solution
  - By local flow mass balance



Hypothetical application





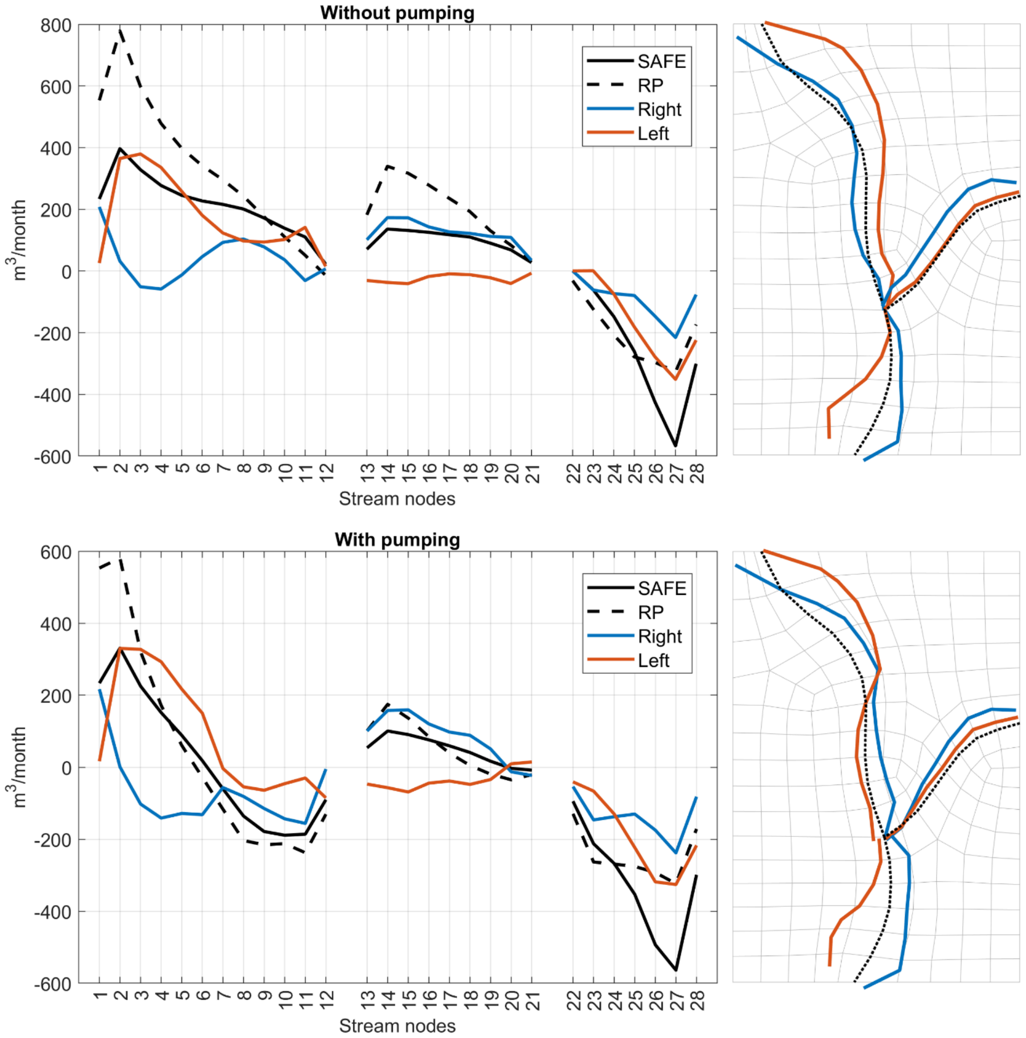
- Simulated with RP and SAFE
- With and without pumping

- Groundwater head at stream nodes is higher with SAFE
- Stream stage difference is negligible but SAFE solution is lower

Hypothetical application

Comparison of **Seepage discharge** (SPD) between SAFE and RP

- RP appears to overestimate SPD for the gaining parts of the streams and underestimate the loosing and disconnected part of the streams
- The low values at the first node of reach 1 and 2 and last of reach 3 is due to the boundary conditions. The area of influence is approximately half compared to the nearby nodes



Asymmetric SPD mapping

- When the left (red) line is at the left side of the river (looking downstream) the distance to river is proportional to Q_s^L (gaining from groundwater) .
- For the river segments that run along the main flow direction (north to south) $Q_s^L \sim Q_s^R$
- For the segments that run diagonally there is significant difference between left and right

Positive seepage discharge (SPD) implies *Gaining* from groundwater

Central Valley – C2VSim

C2VSim:

California Central Valley Groundwater-Surface Water Simulation Model

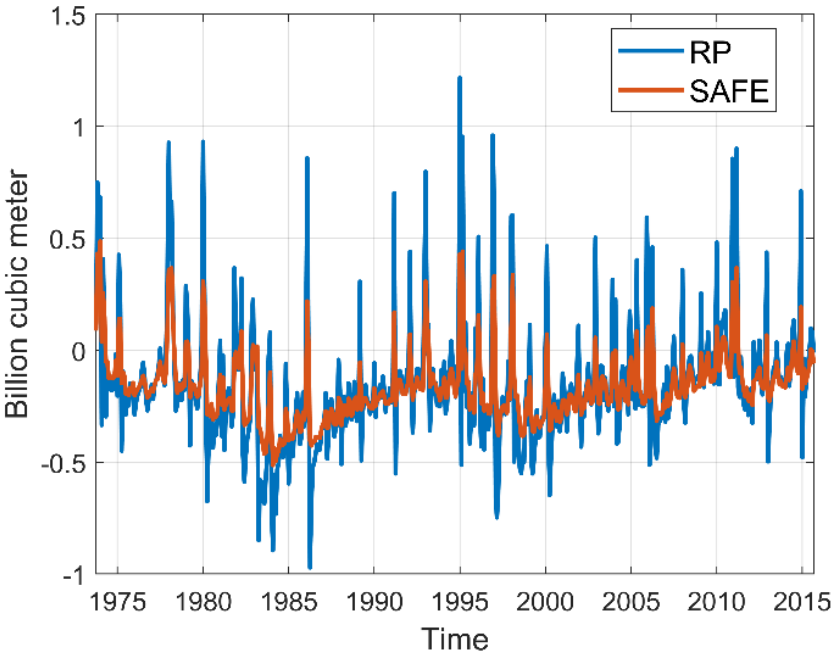
- Coarse Grid version (1,392 elements, ~30 min runtime)
- Fine Grid version (32,537 elements, ~6 hours runtime)
    - 110 Stream reaches
    - 4634 Stream nodes
    - Simulated with Stream package 4.2

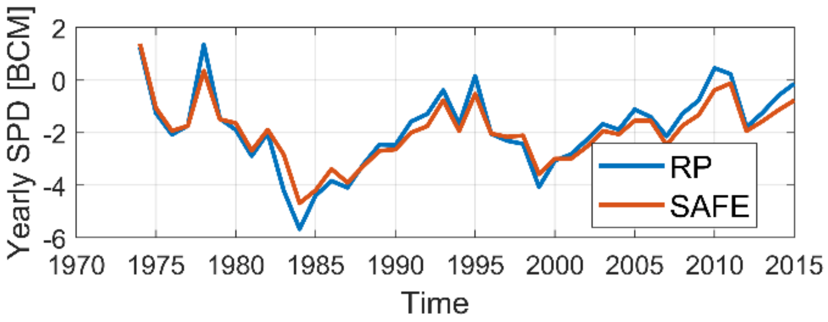
- We run SAFE on both versions, but we show only the fine grid results

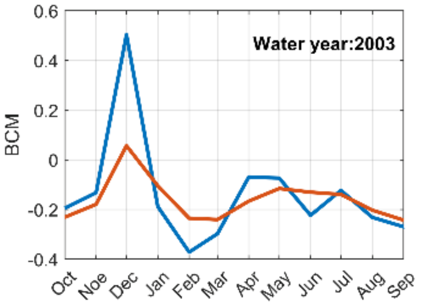
Central Valley – C2VSim

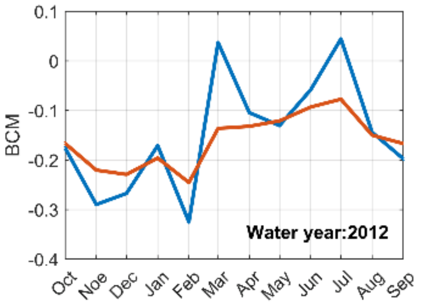
Cumulative comparison over stream nodes of stream aquifer interaction SAFE and RP

- The RP monthly variation is considerably higher than SAFE
- Yearly volumes are very similar
- Overall SAFE method calculates smaller extreme values
- The difference between Dec 2003 and Jan 2004 is 700 MCM (567 TAF)







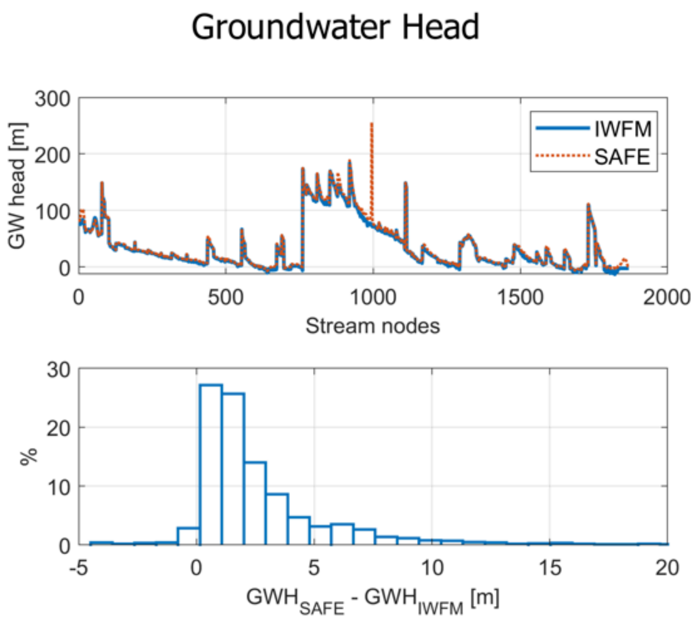


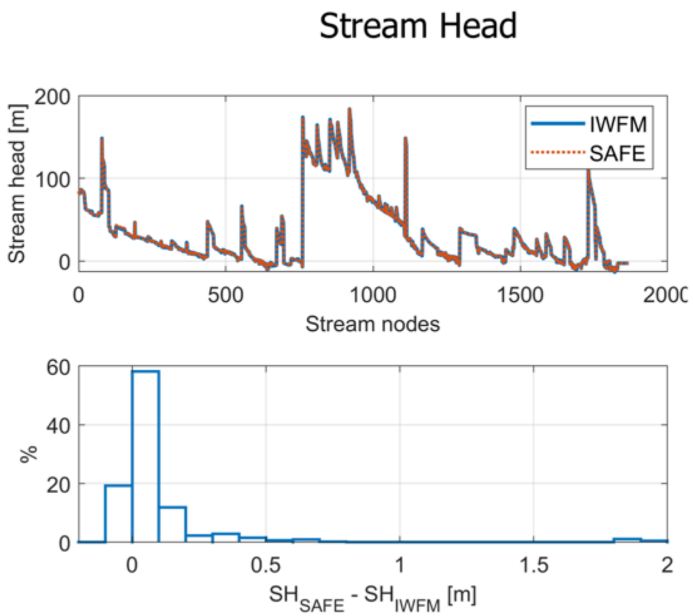
Central Valley – C2VSim

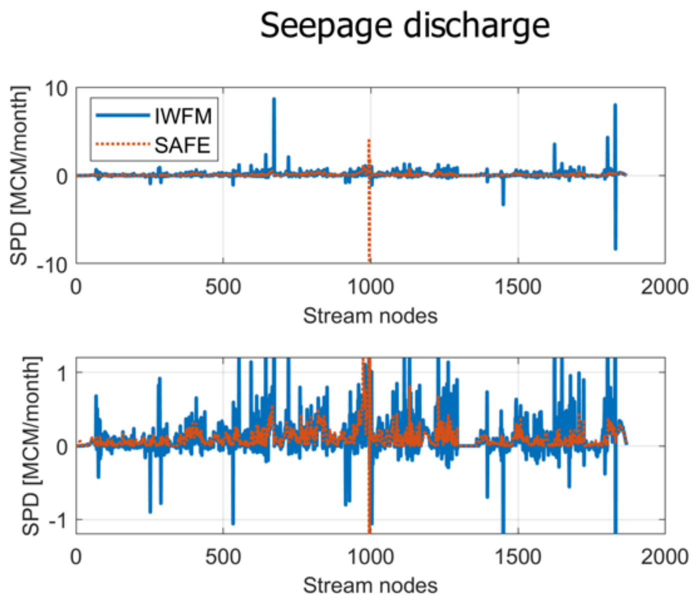
Comparison between SAFE and RP simulation for the last time step

- 40% and 30% of stream node are gaining for SAFE and RP respectively
- SAFE groundwater heads are generally higher than RP
- Stream head is very similar for both methods
- SAFE SPD is less variable from node to node

GWH > SH
Connected Stream

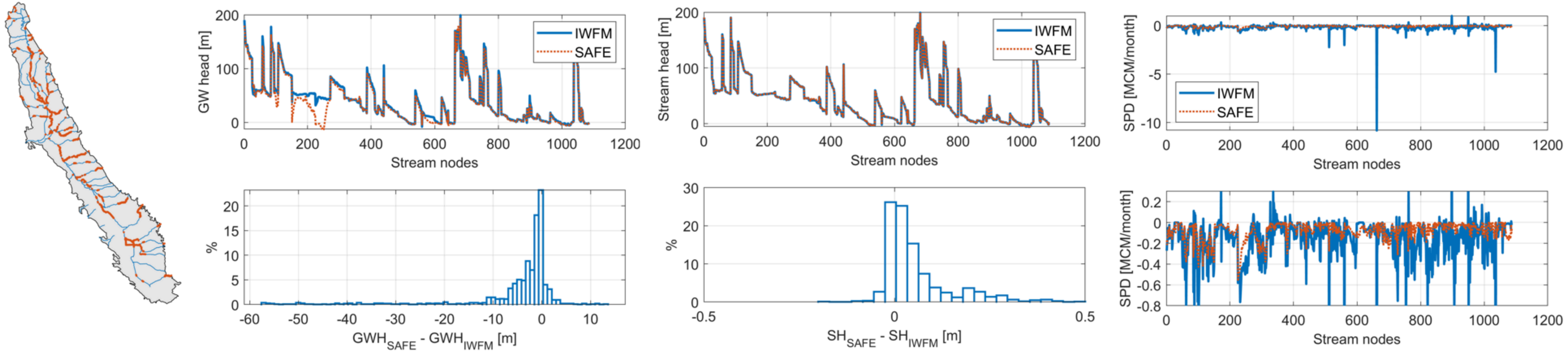




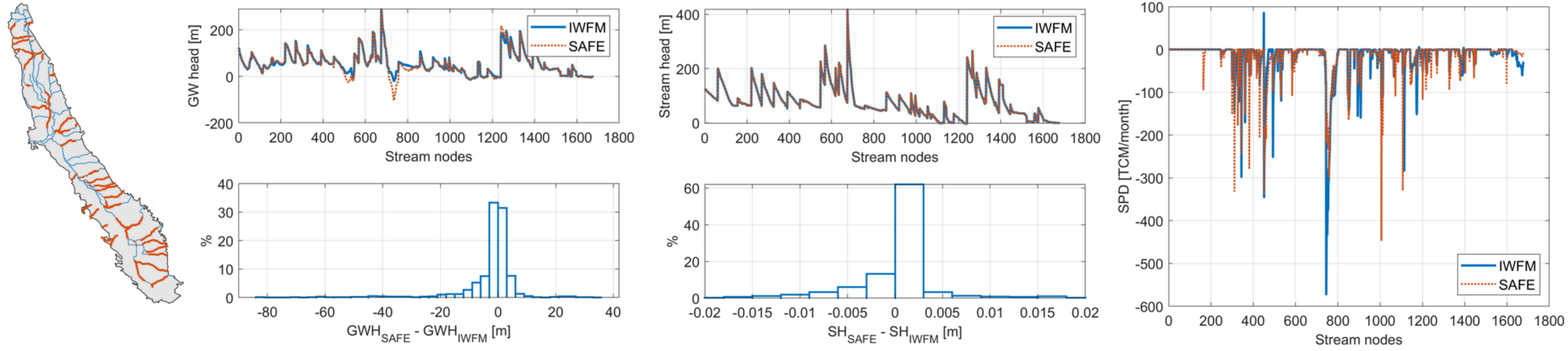


Central Valley – C2VSim

SH > GWH > Hincip
Connected Stream

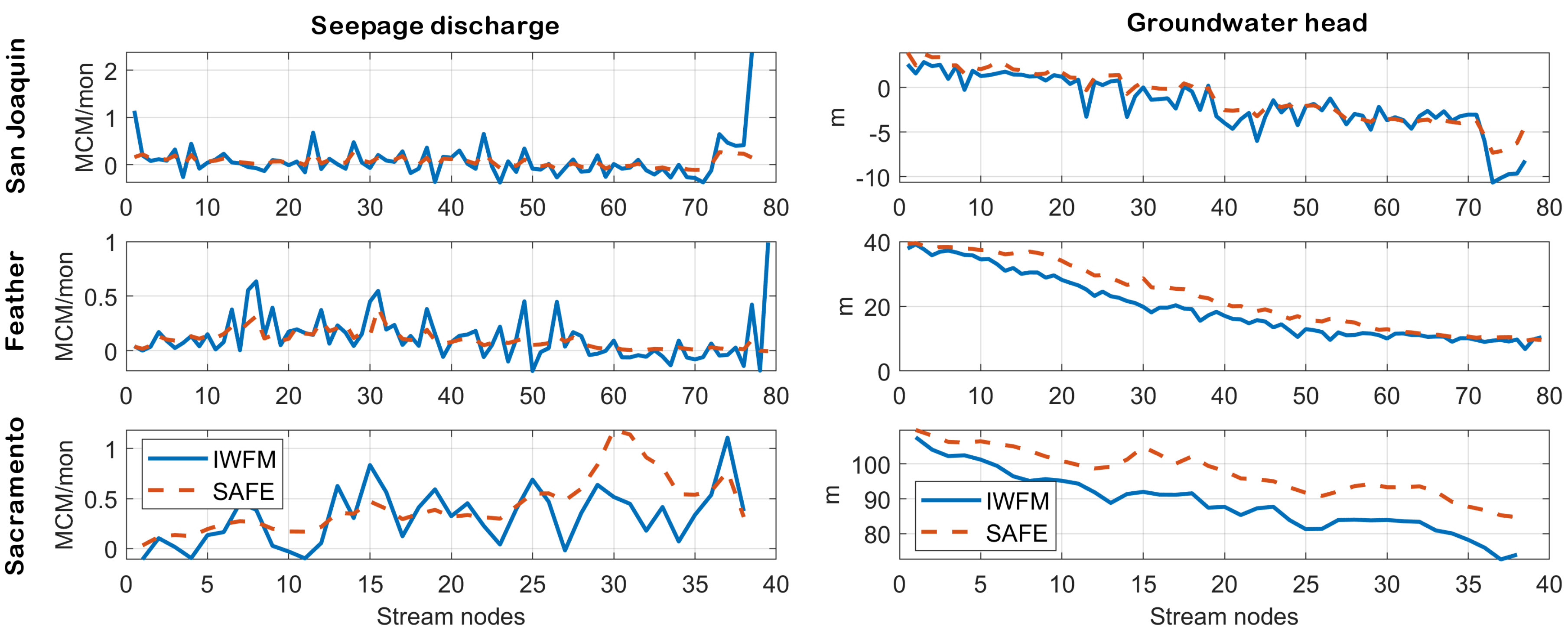


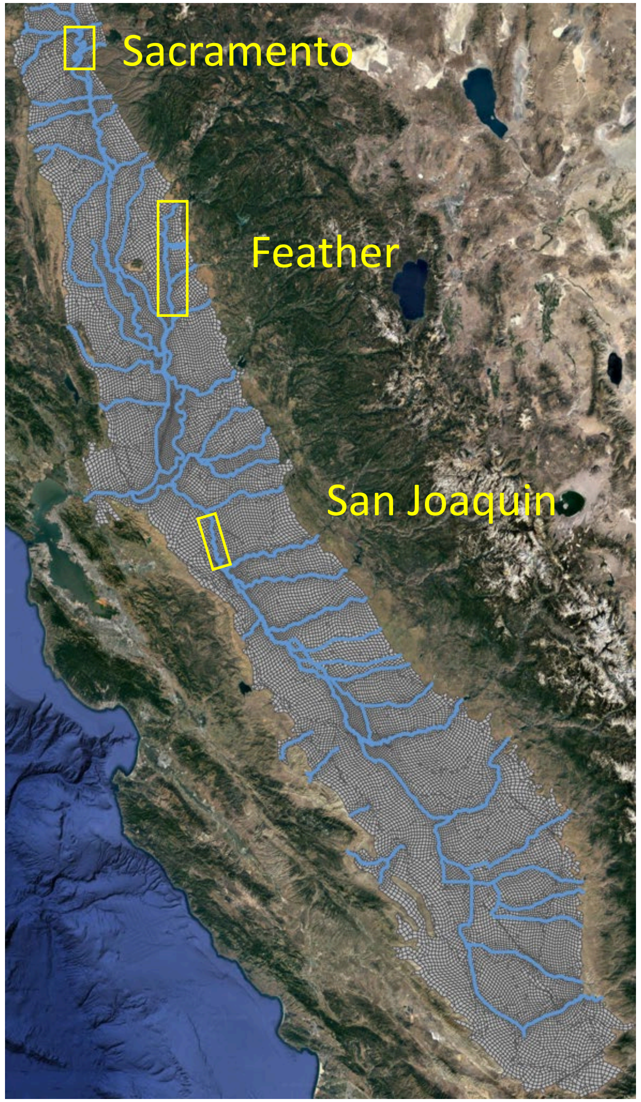
SH > Hincip > GWH
Disconnected Stream



Central Valley – C2VSim

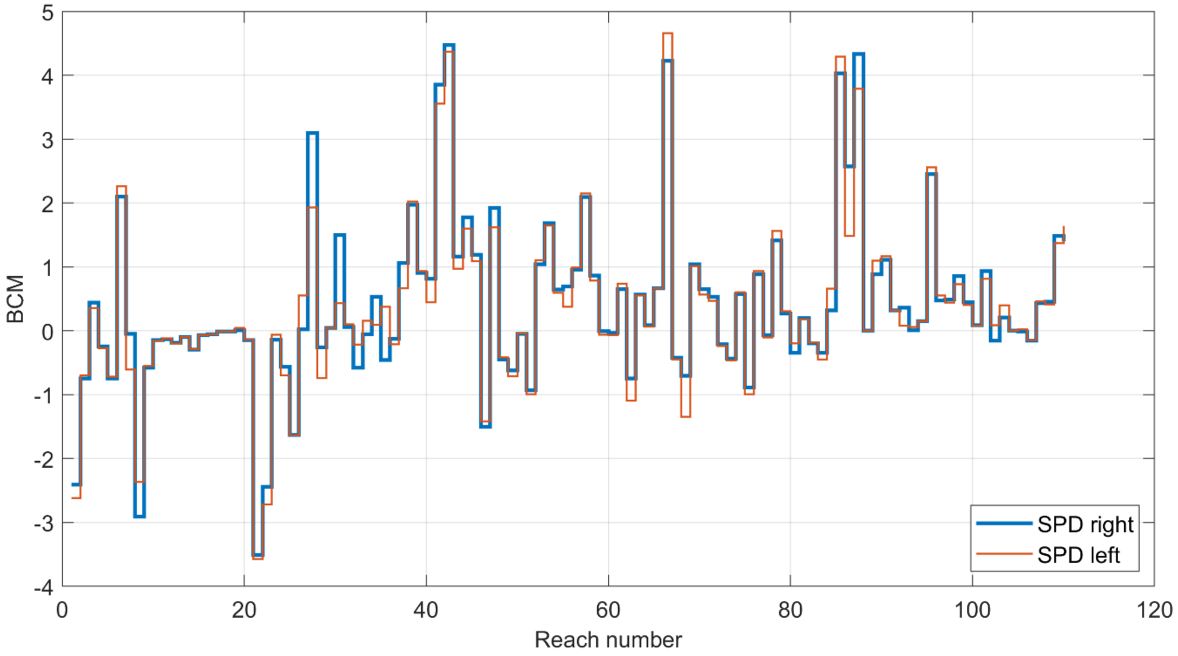
Comparison between SAFE and RP simulation for the last time step for three reaches

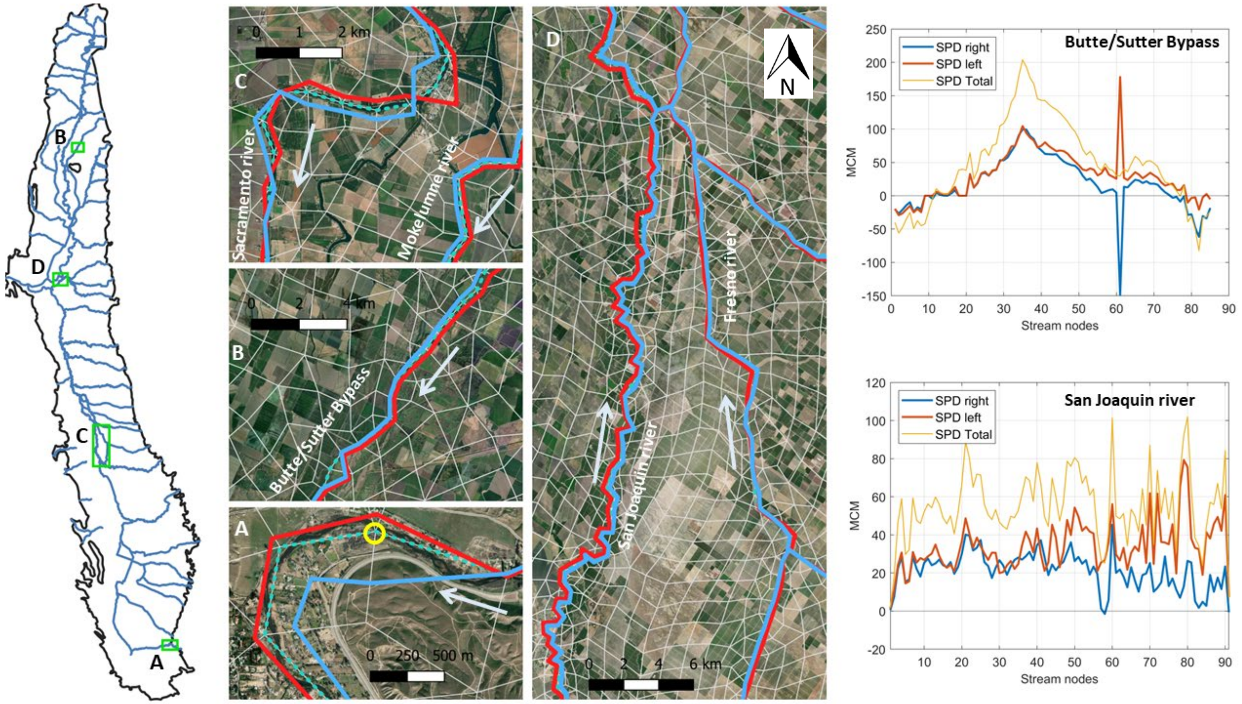




C2VSim Asymmetric quantification

Cumulative comparison between left and right stream-aquifer interaction

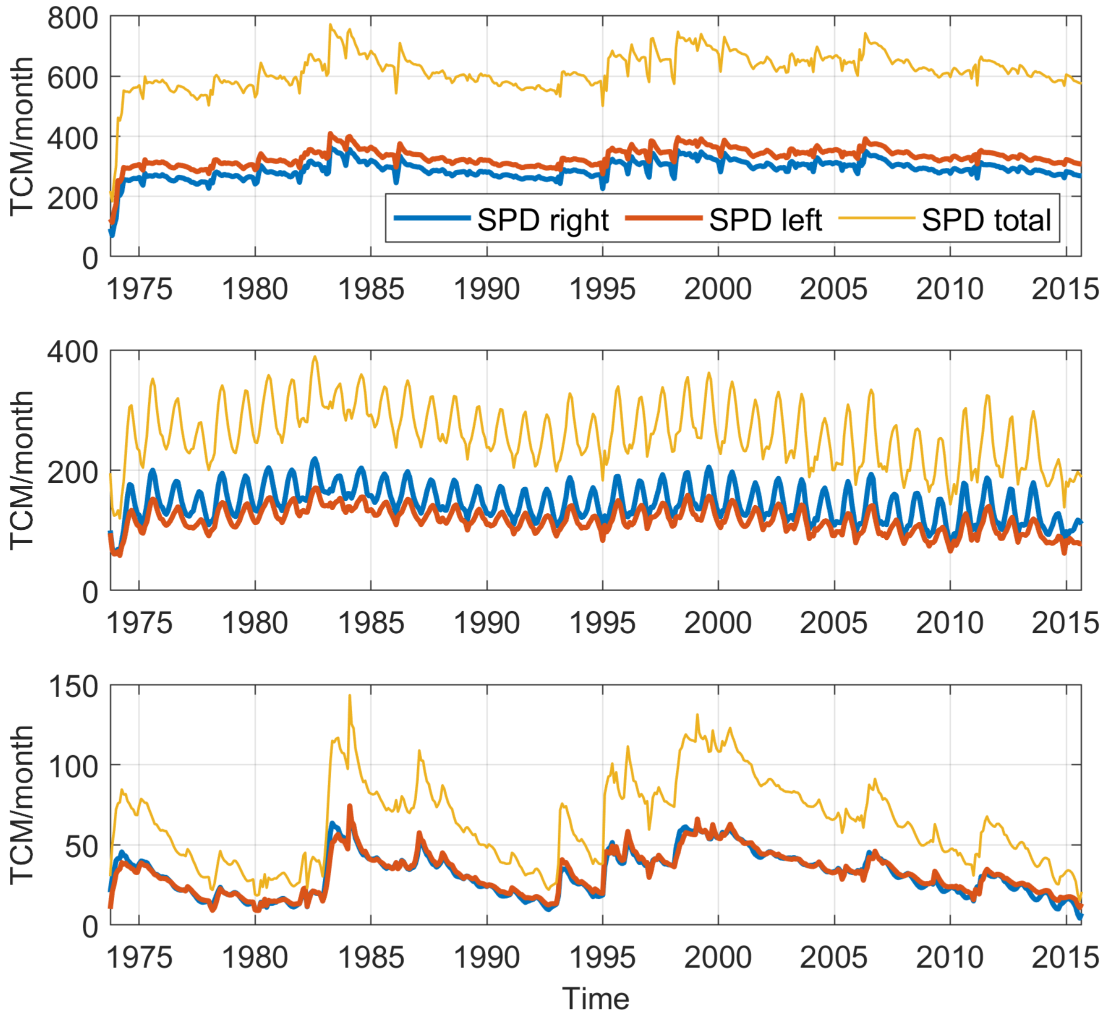




C2VSim Asymmetric quantification

Typical Asymmetric stream aquifer interaction responses at stream node level:

- One side consistently contributes more to stream or aquifer
- One side shows higher variability
- The total volume is split evenly between left and right



Conclusions

- Implement the SAFE method in IWFM code (not yet released)
- Used an improved disconnection criterion
- Extend SAFE method to quantify asymmetric stream-aquifer interaction
- The methodology was applied to a real case study

Future work

- Changes are going to be incorporated into a public release
- Improve the overall converge of the model
- Improve the simulation of the unsaturated connection