Deltares

Enabling Delta Life

Improving hydrological prediction through data assimilation: results from the H2020 IMPREX and eWaterCycle II projects

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Deltares – Operational Water Management / Wageningen University & Research

WAGENINGEN UNIVERSITY & RESEARCH

Introduction

- Background DA/hydrological forecasting work
- Results IMPREX
    - model
    - DA lake levels
    - DA streamflow all Rhine tributaries
- Conclusions
- Outlook Ewatercycle II project

Challenges

- What triggered me to have an interest in hydrological data assimilation?

http://www.robots.ox.ac.uk/~misard/condensation.html

Hydrological Model?

Which algorithm?

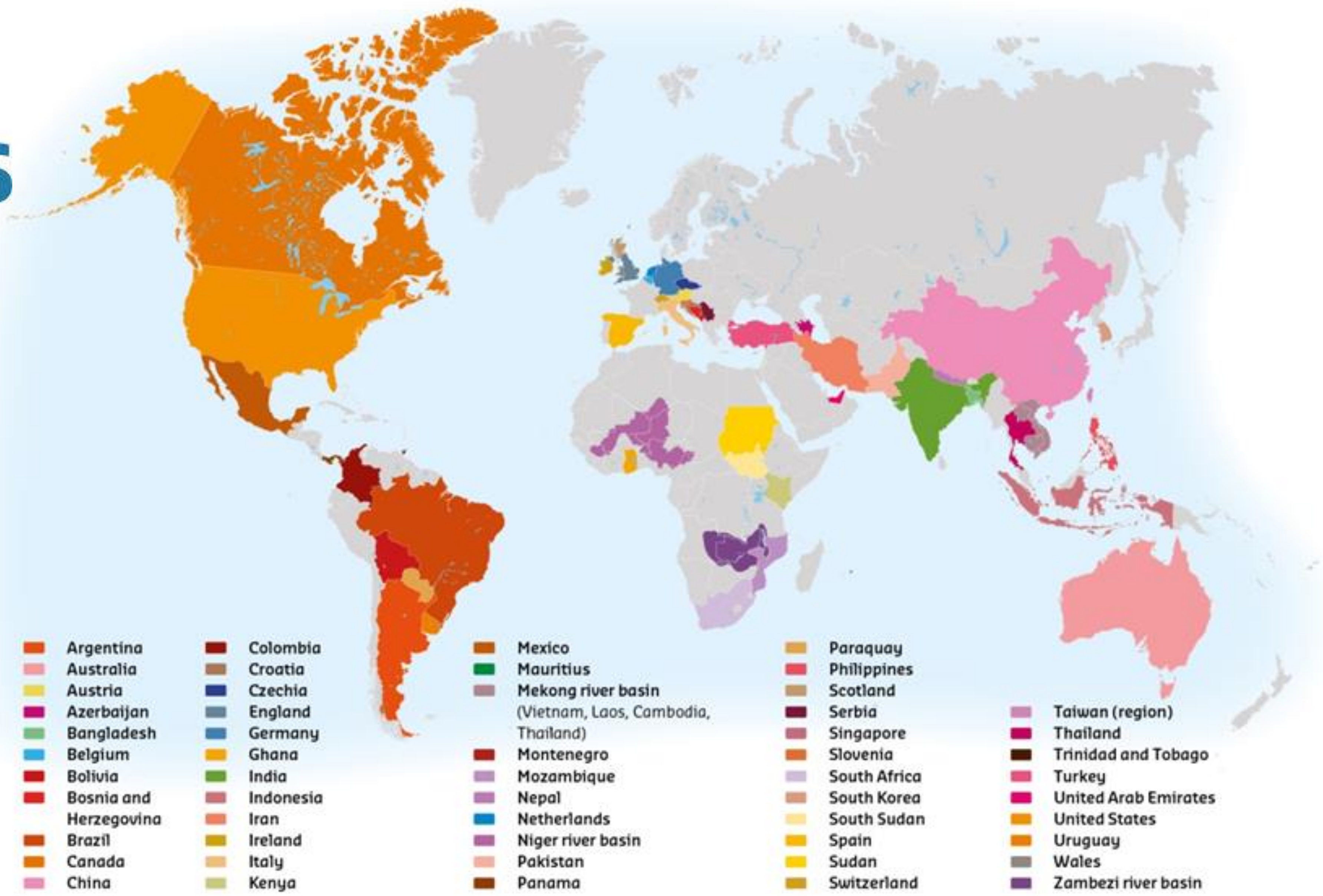
Which measurements?

How to define the uncertainties?

Operational applicability?

How much improvement spatially and as function of leadtime?

Delft-FEWS

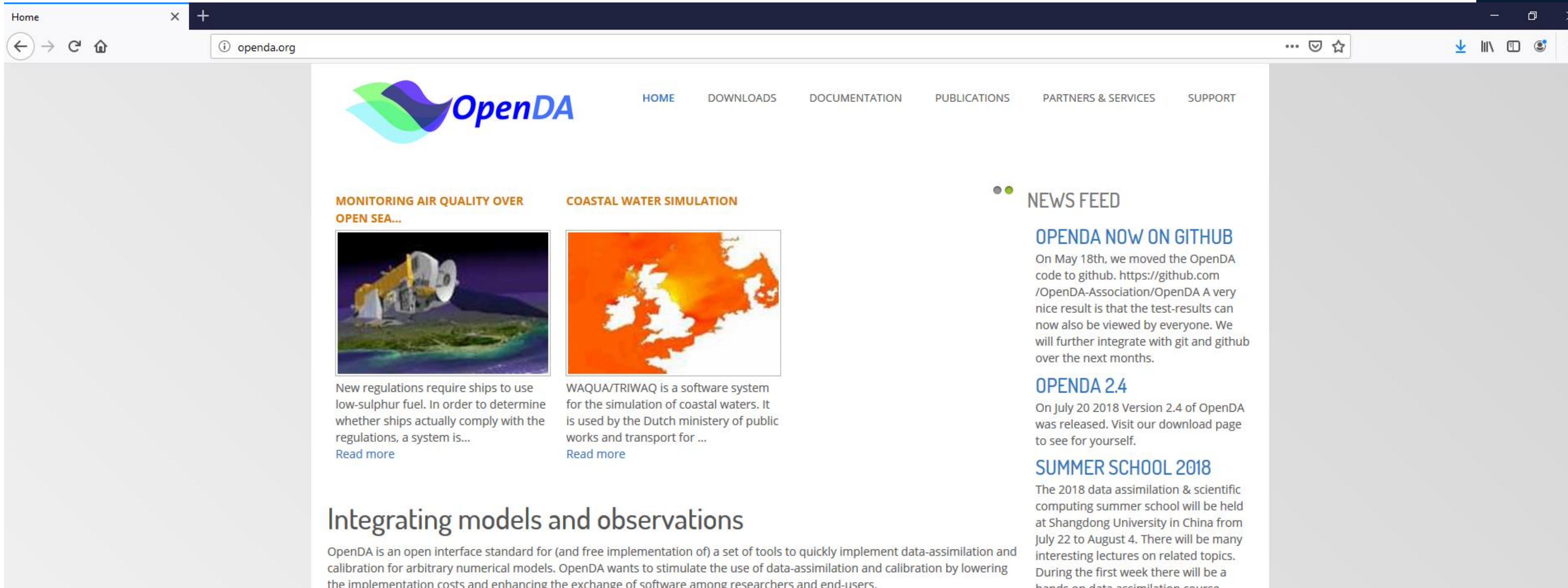


Argentina
Australia
Austria
Azerbaijan
Bangladesh
Belgium
Bolivia
Bosnia and Herzegovina
Brazil
Canada
China
Colombia
Croatia
Czechia
England
Germany
Ghana
India
Indonesia
Iran
Ireland
Italy
Kenya
Mexico
Mauritius
Mekong river basin (Vietnam, Laos, Cambodia, Thailand)
Montenegro
Mozambique
Nepal
Netherlands
Niger river basin
Pakistan
Panama
Paraguay
Philippines
Scotland
Serbia
Singapore
Slovenia
South Africa
South Korea
South Sudan
Spain
Sudan
Switzerland
Taiwan (region)
Thailand
Trinidad and Tobago
Turkey
United Arab Emirates
United States
Uruguay
Wales
Zambezi river basin

What is OpenDA?

- OpenDA is an open interface standard for (and free implementation of) a set of tools to quickly implement data-assimilation and calibration for arbitrary numerical models. OpenDA wants to stimulate the use of data-assimilation and calibration by lowering the implementation costs and enhancing the exchange of software among researchers and end-users.

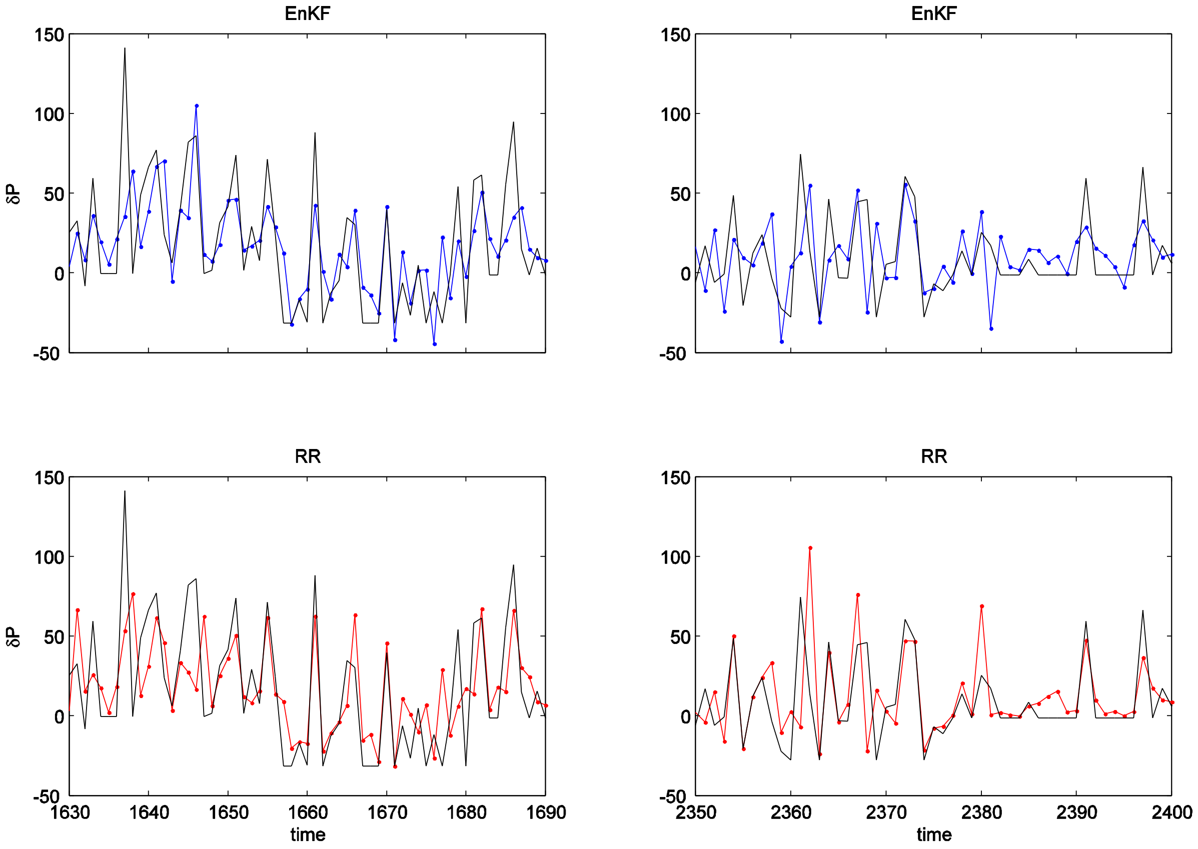
- See OpenDA.org



Current=>IMPREX=> and beyond

	Current	IMPREX	and beyond
Flood Forecasting	Lumped HBV96 -hourly -height zones linked to station certain height -fixed PET profiles -fixed interception (g/f) -big calibration effort (last time 2008) -many correction factors, WB fiddling -closed source	wflow_hbv -hourly, 6hourly, daily -distributed P, T, PET - PET formulation harmonized with rest of RWSOS -ensemble DA -open source	wflow_sbm -hourly, 6hourly, daily -distributed P, T, PET -improve fidelity process formulations -LAI, Landuse etc fully distributed -PTFs -ensemble DA -forecasted P, Eref, T -open source
Policy	HBV96 -daily -big calibration effort (completed 2014) -multiple parameter sets -lumped P&T generator	wflow_hbv -daily or subhourly -distributed P, T, PET -multiple parameter sets	wflow_sbm -daily or subhourly -landuse scenarios -multiple parameter sets?

Lumped hydrological model HBV-96 & Algorithms & Noise



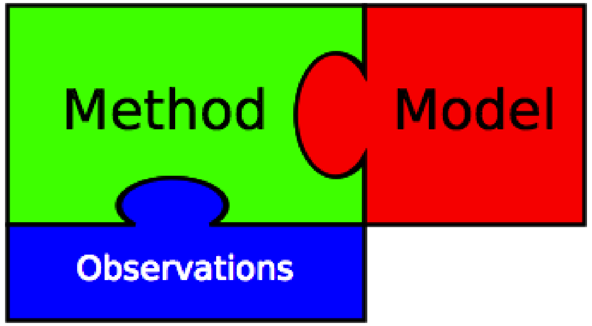
time

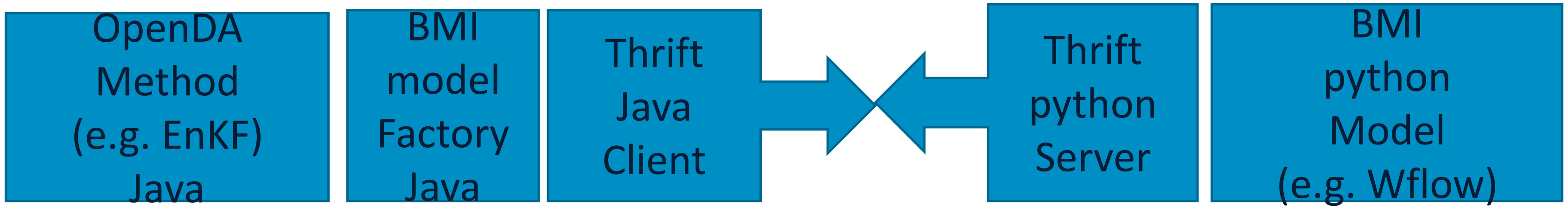
Weerts and El Serafy, WRR, 2006

- Can we estimate errors in precipitation? Yes, but..
- need of Markov property state x_{t+1} depends only on x_t
- EnKF robust for operational purposes, PF more likely for academic studies (in hydrology)
- When freezing outflow governed by groundwaterstore/bucket

OpenDA-WFLOW

OpenDA is an open source toolbox for data assimilation and parameter calibration in a generic modeling context.





Drost et al., 2015

Weerts et al., (in prep)

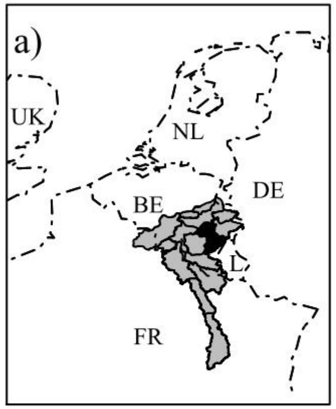
BMI=> http://csdms.colorado.edu/wiki/BMI_Description

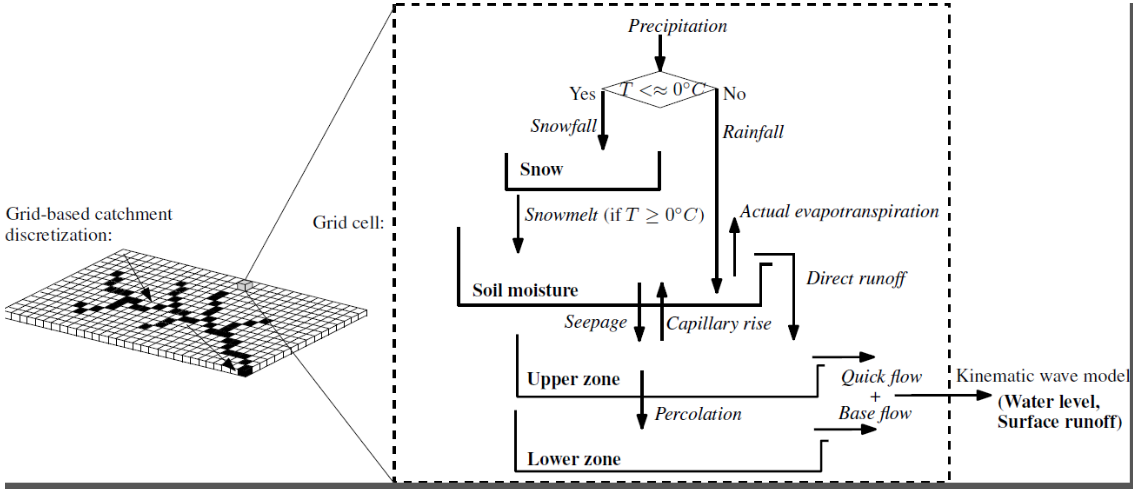
https://github.com/openstreams/wflow
https://wflow.readthedocs.io/en/latest/

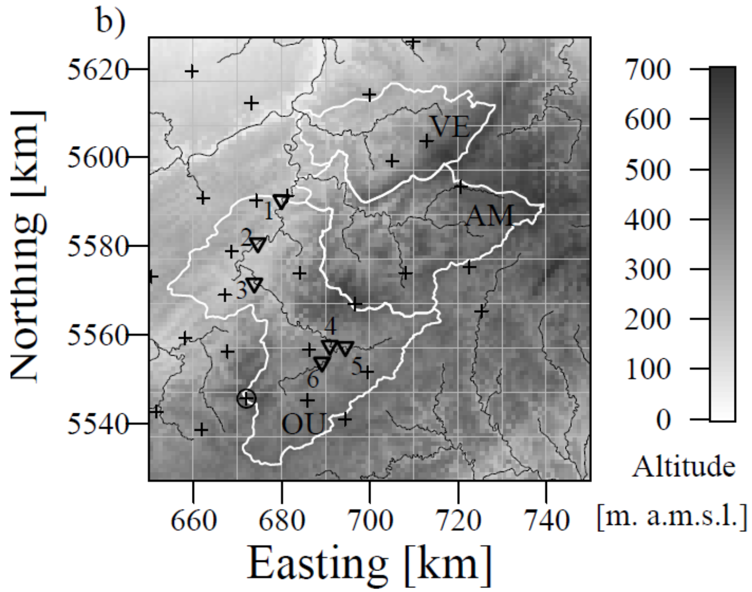
distributed models (wflow_hbv)

- First effort using distributed model with HBV clone (wflow_hbv)

Rakovec et al., HESS, 2012, Rakovec et al.,HESS, 2015



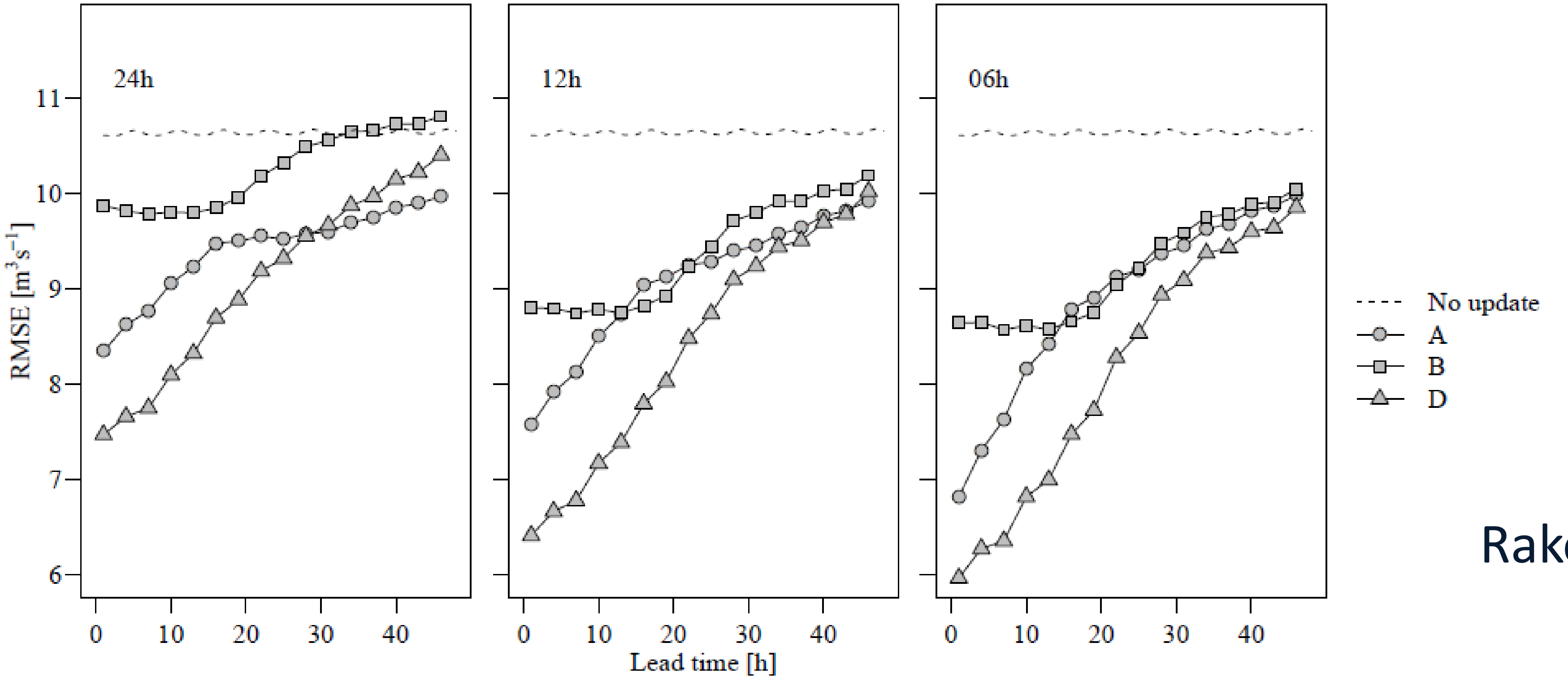




1 km^2

- Kinematic wave routing (state x_{t+1} depends only on x_t) => how much information does the discharge have about states upstream?

Distributed models (wflow_hbv) II



Rakovec et al., 2012

Best results in terms of the RMSE were achieved using all observations, which includes all six discharge gauges. Given the travel time of the catchment, an updating frequency of 12 h seems to be the most appropriate.

Most sensitivity in routing stores

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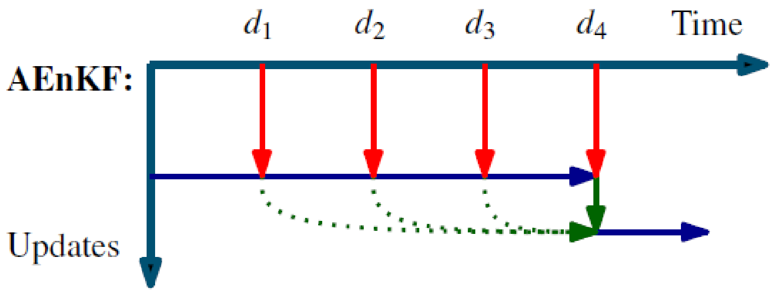
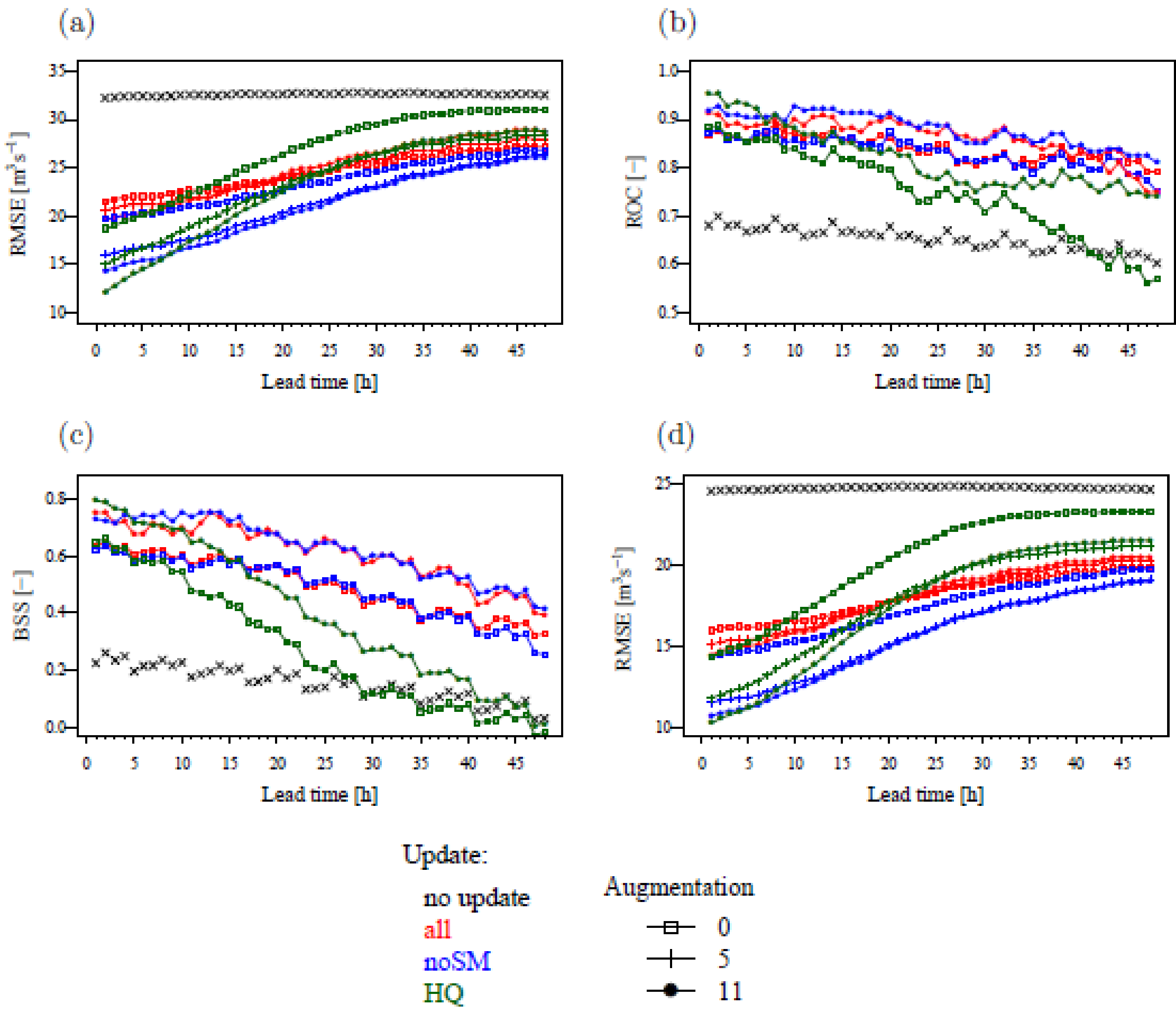
Algorithm (Asynchronous EnKF) and backpropogation of information

Asynchronous Ensemble Kalman Filter (*Sakov et al., 2010*) updates model at the analysis step using past observations over a time window:



The Asynchronous EnKF is particularly attractive from a forecasting perspective as more observations can be used with **hardly any extra additional computational time!**

Rakovec et al., HESS, 2015



Current=>IMPREX=> and beyond

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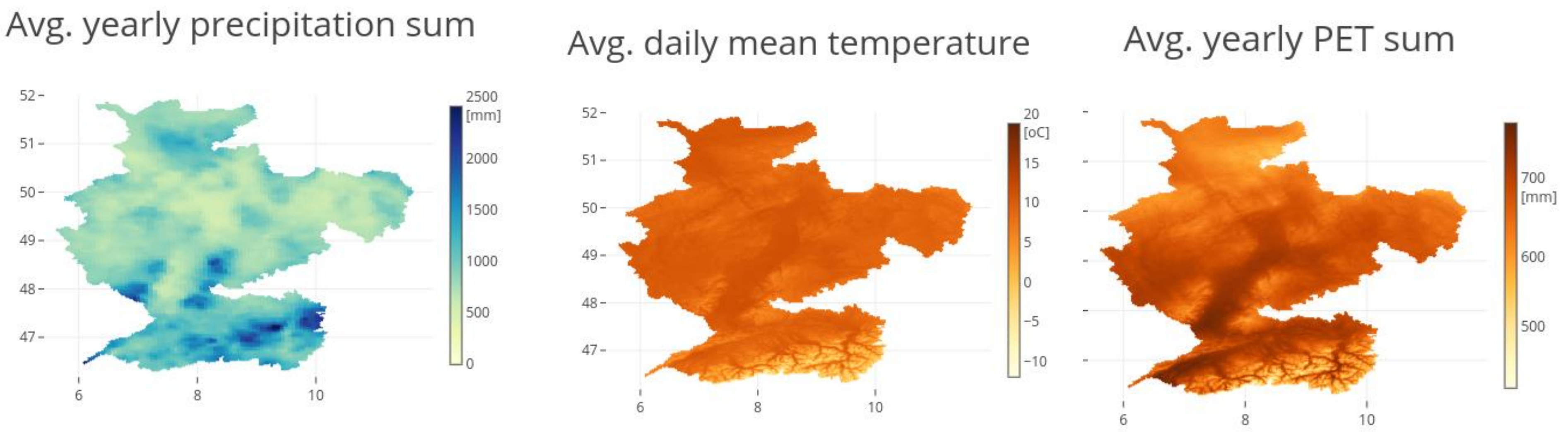
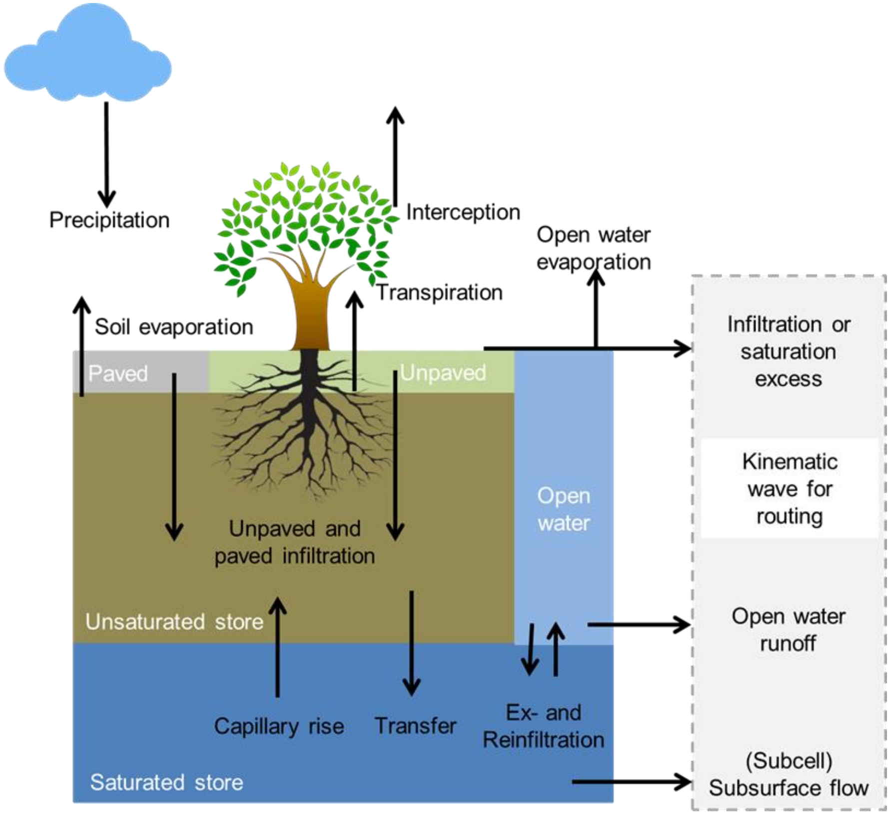
Policy	HBV96 -daily -big calibration effort (completed 2014) -multiple parameter sets -lumped P&T generator	wflow_hbv -daily or subhourly -distributed P, T, PET -multiple parameter sets	wflow_sbm -daily or subhourly -landuse scenarios -multiple parameter sets?

Forcing and other data



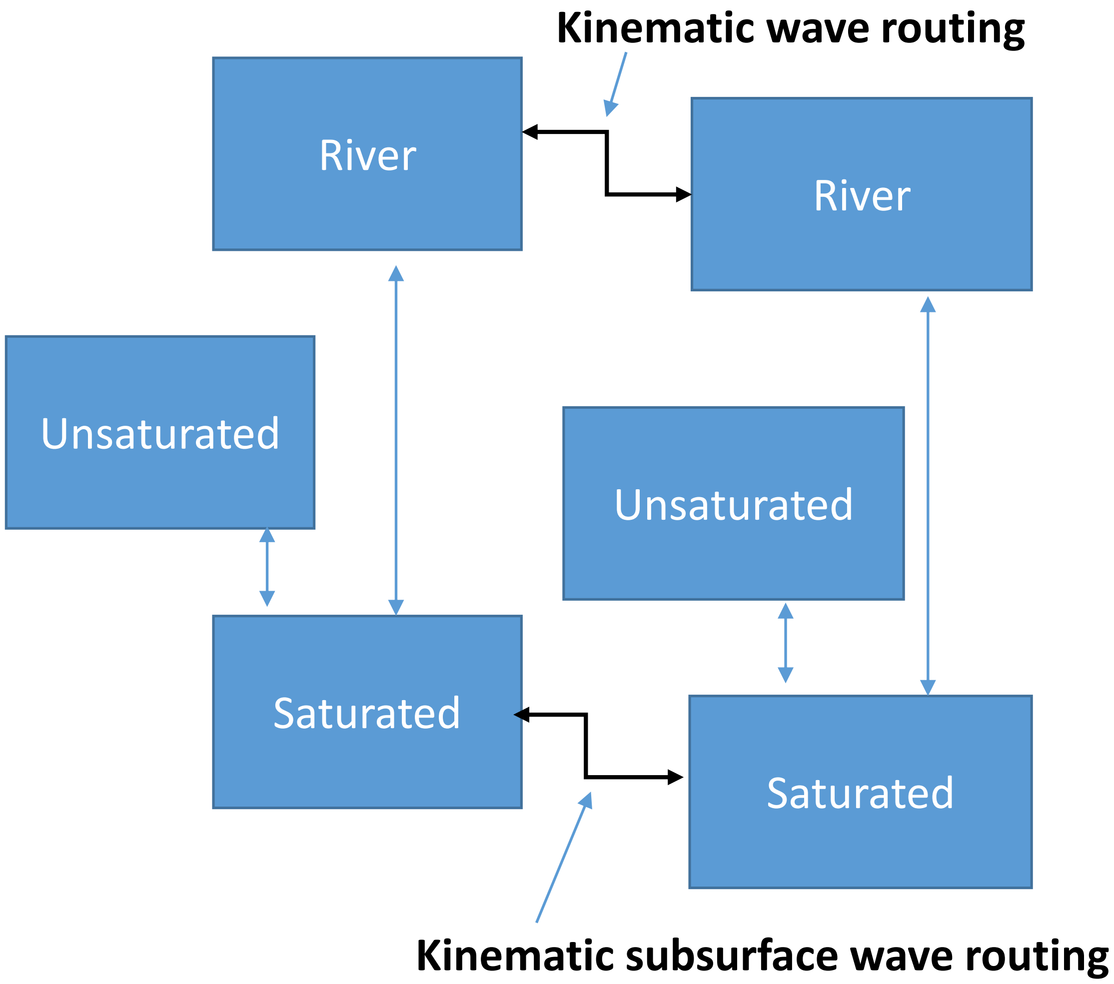
- Forcing (6 hourly at 1200x1200 m^2):
  - From hourly P (genRe),T, PET for period 1996-2015 [van Osnabrugge et al., 2017, 2019]
- Soil data, e.g.:
  - ISRIC global SoilGrids 250 m [Hengl et al., 2017]
  - ESDAC for Eurasia [ESDAC, 2004; Panagos et al., 2012]
  - Corine for Landuse

wflow_sbm (simple bucket model)



- Parameters represent environmental characteristics
- Bucket model with **kinematic wave surface and subsurface flow** between cells
- ET and interception losses (Gash/Rutter)
- Percolary rise
- Flow routing on PCRaster D8-network [Karssenberg, et al., 2010]
- Use of multiple soil layers
- Glaciers
- Reduction coefficient for ET_{act} from the unsaturated zone [Feddes et al., 1978]

wflow_sbm



Similar to TopKapi, G2G

Hypothesis and approach taken

- Hypothesis: we can use point scale PTFs from pedometric community at 250m (based on soilgrids, Hengl et al. 2017);
- Use upscaling techniques (similar to what is used in MPR and others):
  - to achieve flux matching
  - to obtain consistent seamless parameters across scales;
- Validate this approach using a high resolution distributed hydrological model;

Upscaling rules

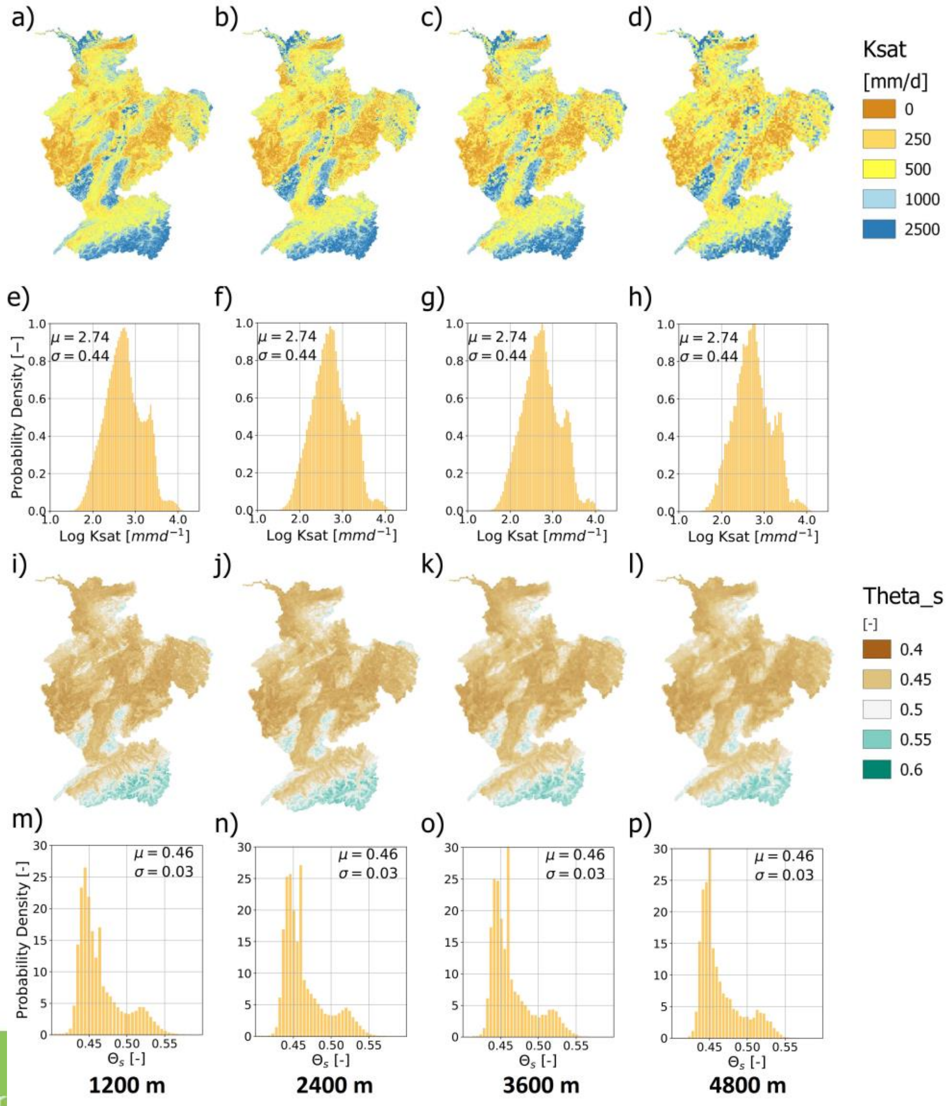
Parameter	Pedo-transfer function by	Upscaling operator	Additional notes
c	Rawls and Brakensiek (1989)	log A	λ upscaled with log A, c determined from λ at model resolution
Kext	Van Dijk and Bruijnzeel (2001)	A	Look-up table from land cover
KsatVer	Brakensiek et al. (1984)	log A	
LAI	Myneni et al. (2015)	A	
M			Derived as exponential decay-function from KsatVer at 7 depths
N	Engman (1986) and Kilgore (1997)	A	Look-up table from land cover
N_River	Z. Liu et al. (2005)		Derived at model resolution, depends on Strahler order
RootingDepth	Schenk and Jackson (2002); Fan et al. (2016)	A	d_{75} rooting depth
Sl	Pitman (1989) and S. Liu (1998)	A	Look-up table from land cover
Slope	(Farr et al., 2007)	A	PCRaster-functionality (Karssenberg et al., 2010), based on DEM
SoilThickness	Hengl et al. (2017) and ESDAC (2004)	A	
Swood	Pitman (1989) and S. Liu (1998)	A	Look-up table from land cover
thetaR	Tóth et al. (2015)	A	
thetaS	Tóth et al. (2015)	A	

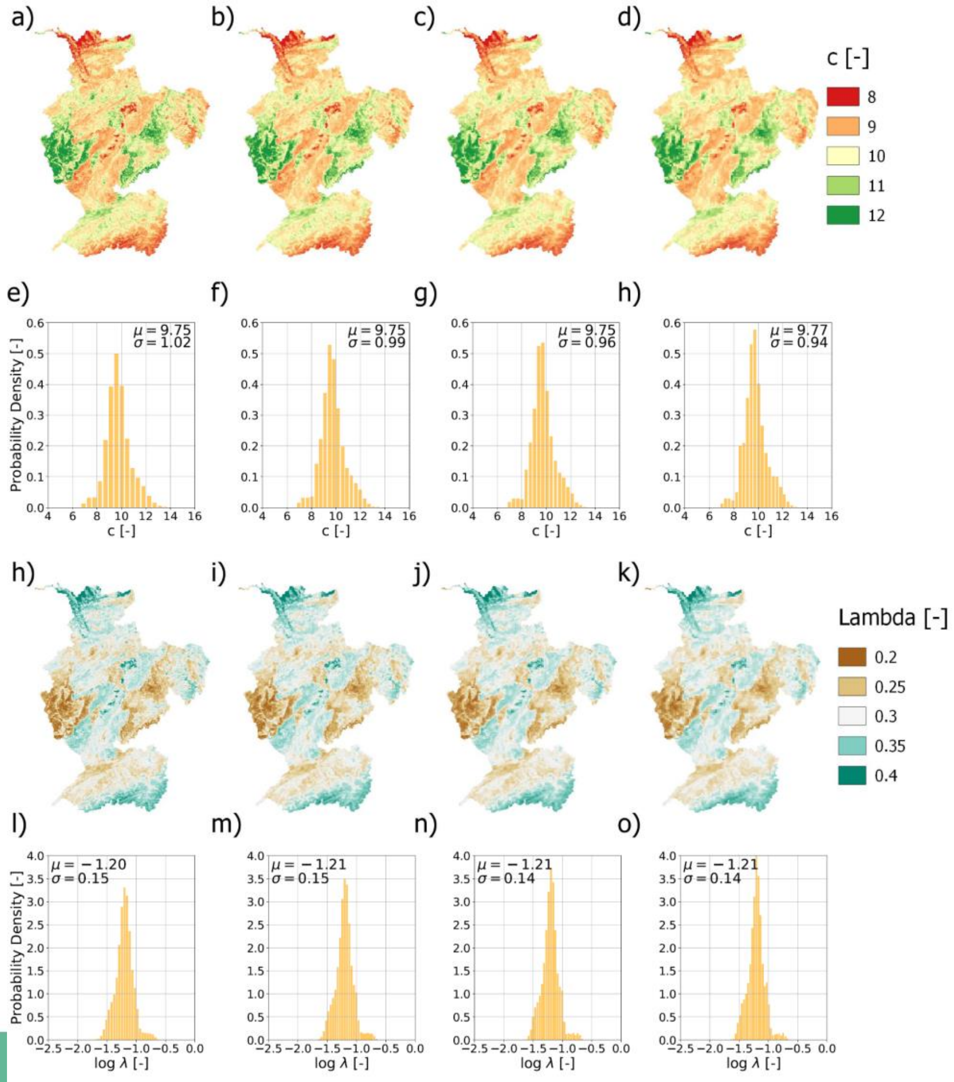
Imhoff et al., 2019 resubmitted to WRR

Results

Imhoff et al., 2019 resubmitted to WRR

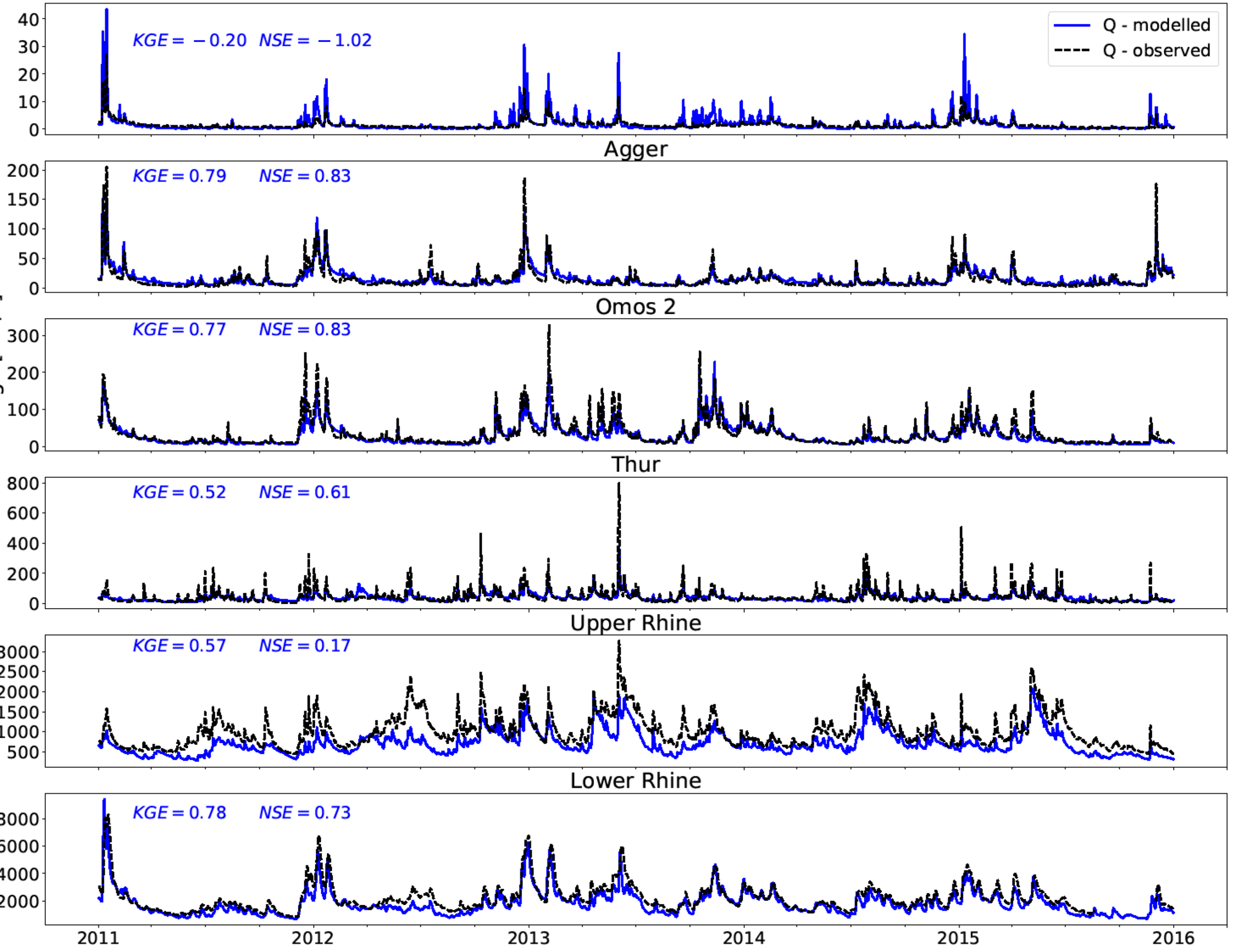
model parameters at different scales

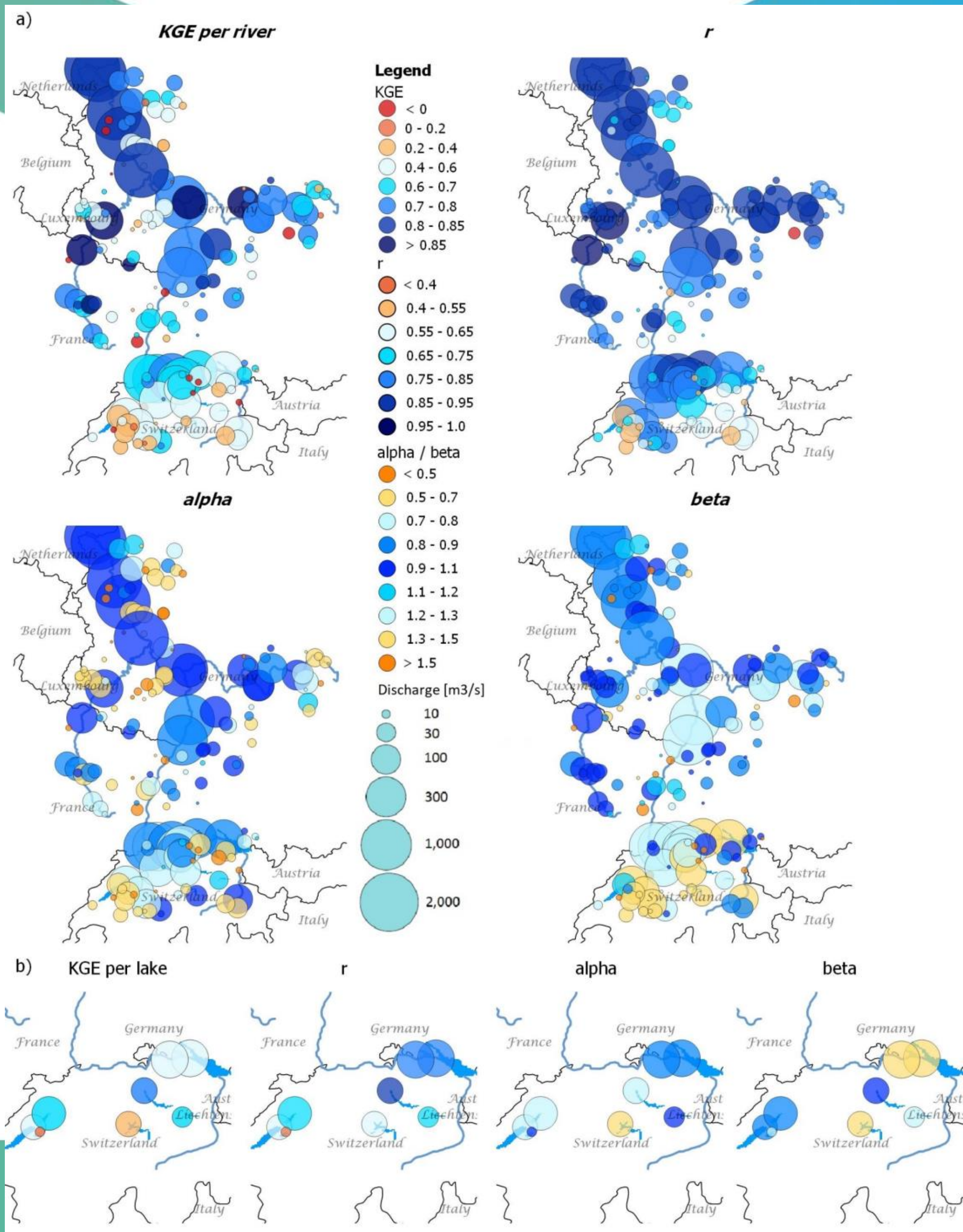




Imhoff et al., 2019 resubmitted to WRR

wflow sbm (at 1200m)

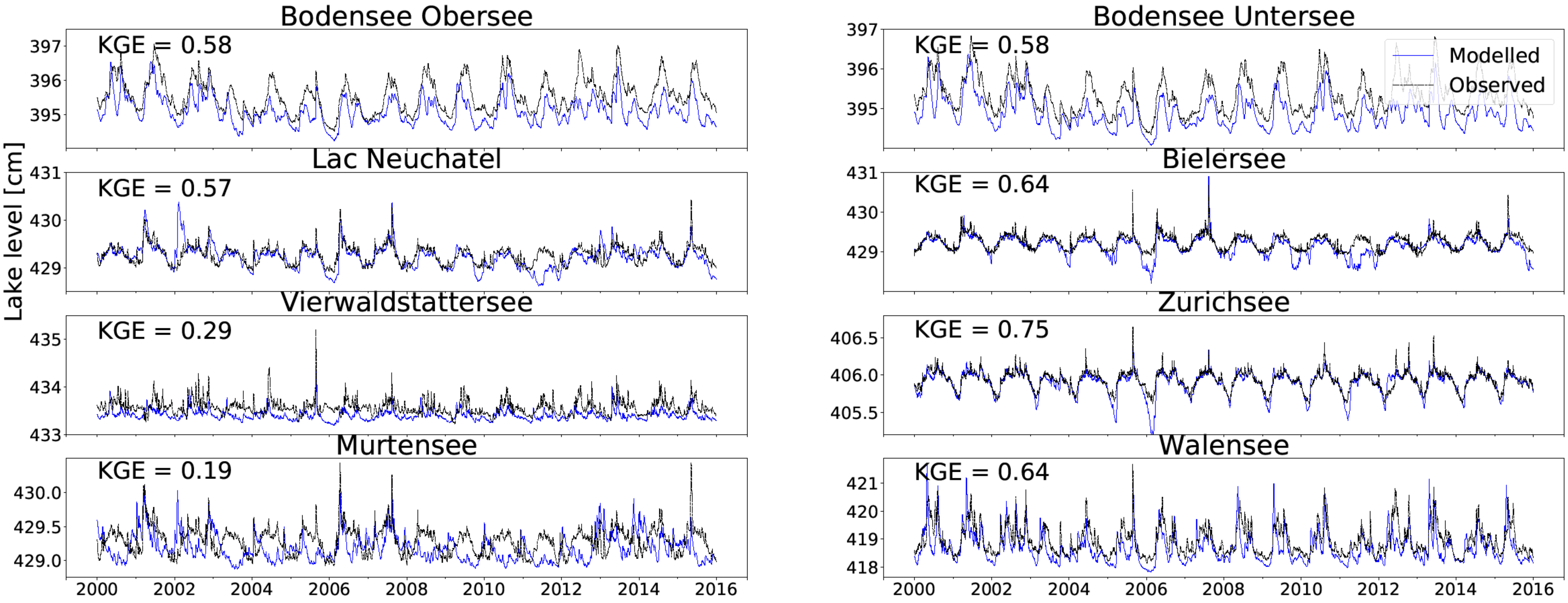




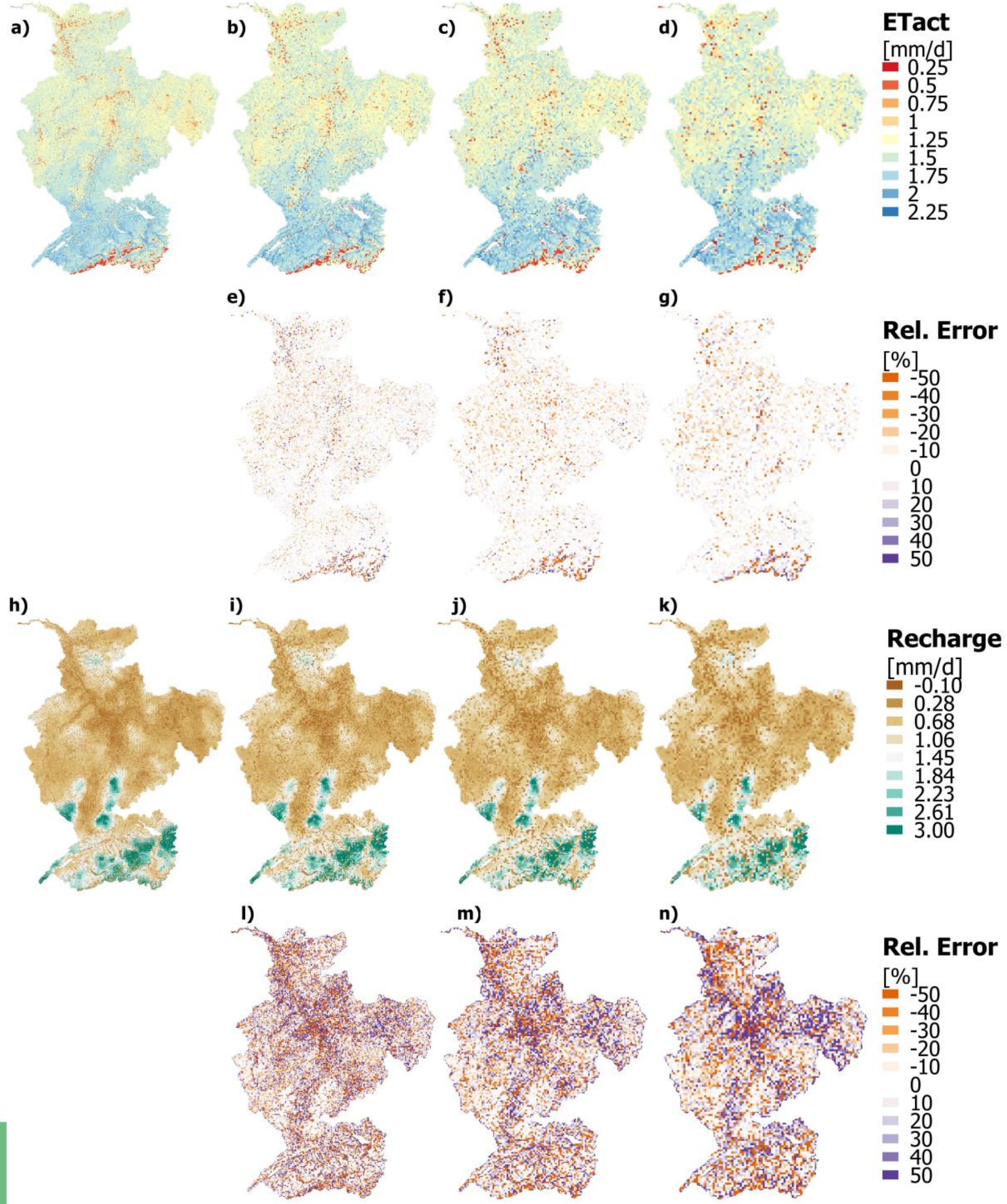
@imprex_eu

$$\textbf{KGE}=\sqrt{(1-r)^2+(1-\alpha)^2+(1-\beta)^2}$$

Performance Lakes

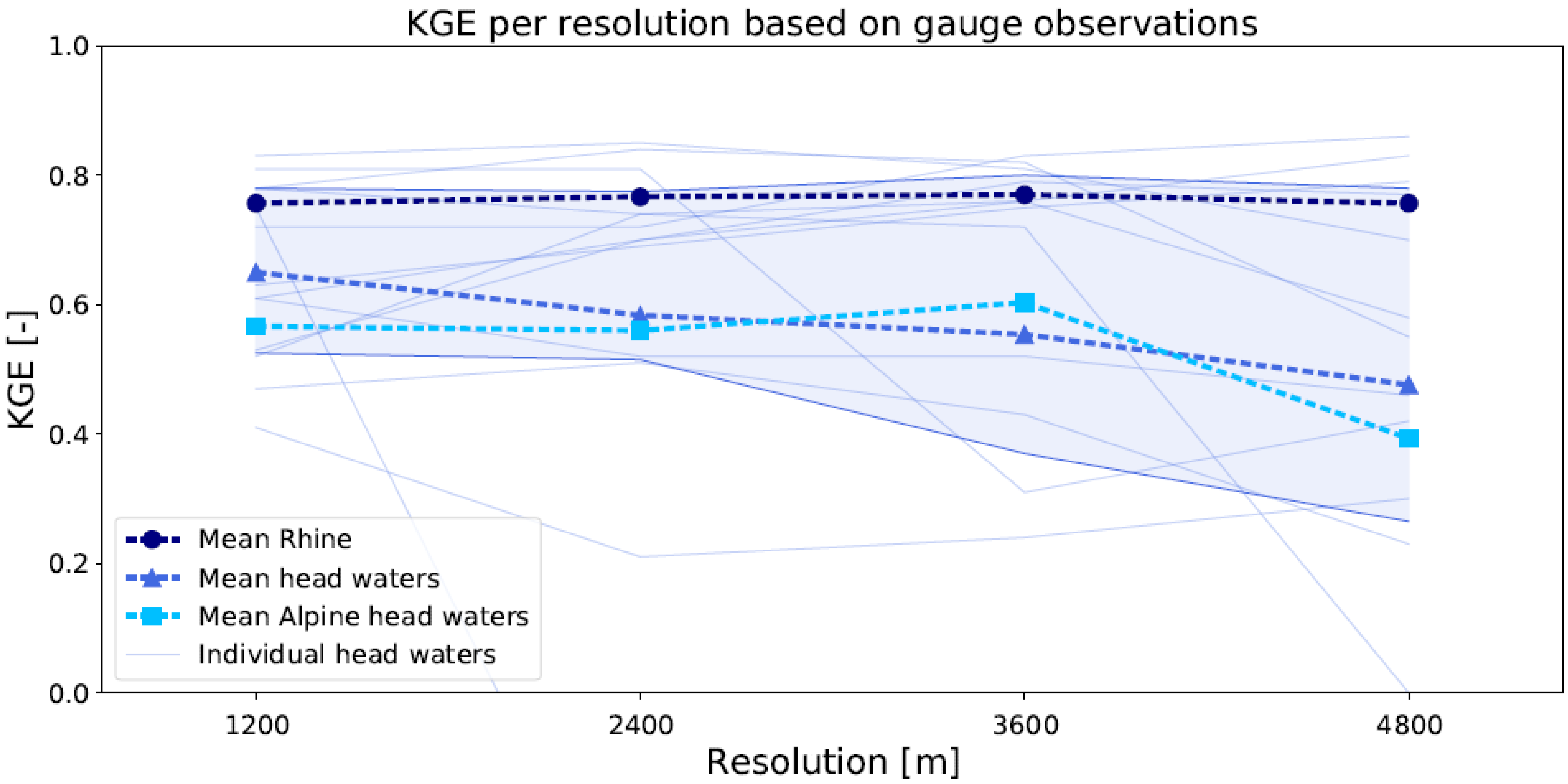


Fluxmatching



Imhoff et al., 2019 resubmitted to WRR

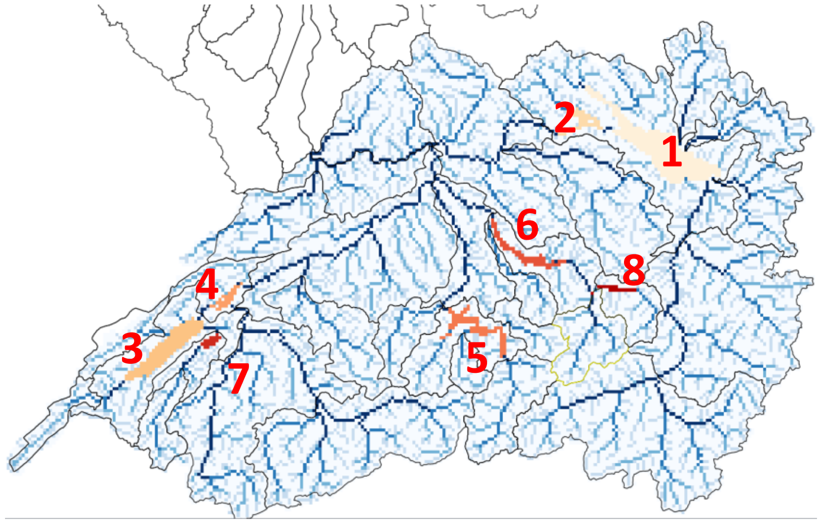
KGE at different model resolutions

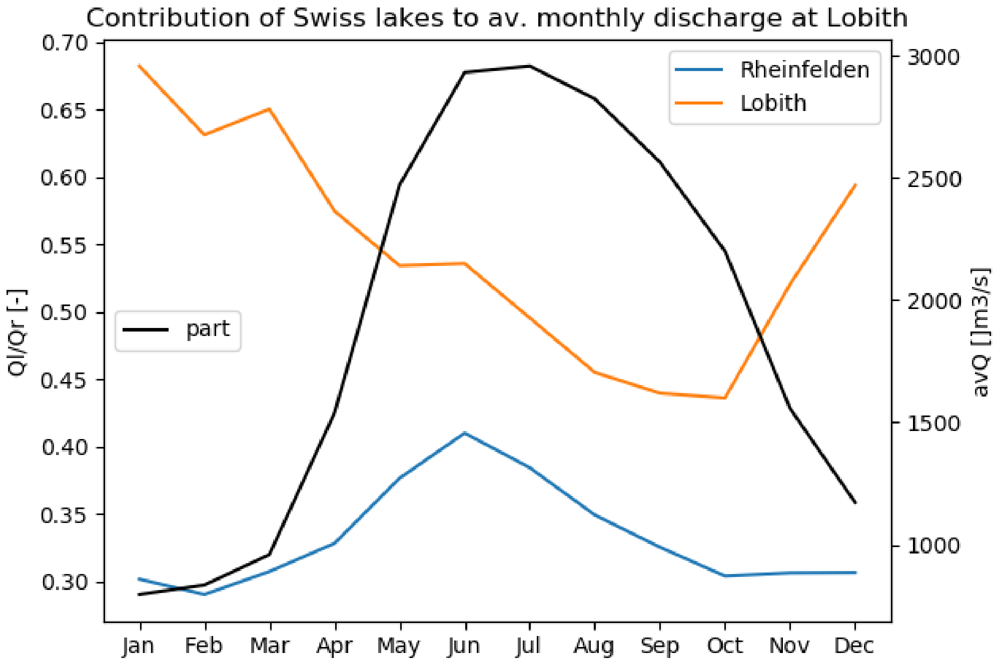


Imhoff et al., 2019 resubmitted to WRR

Assimilating waterlevels of 8 Swiss lakes

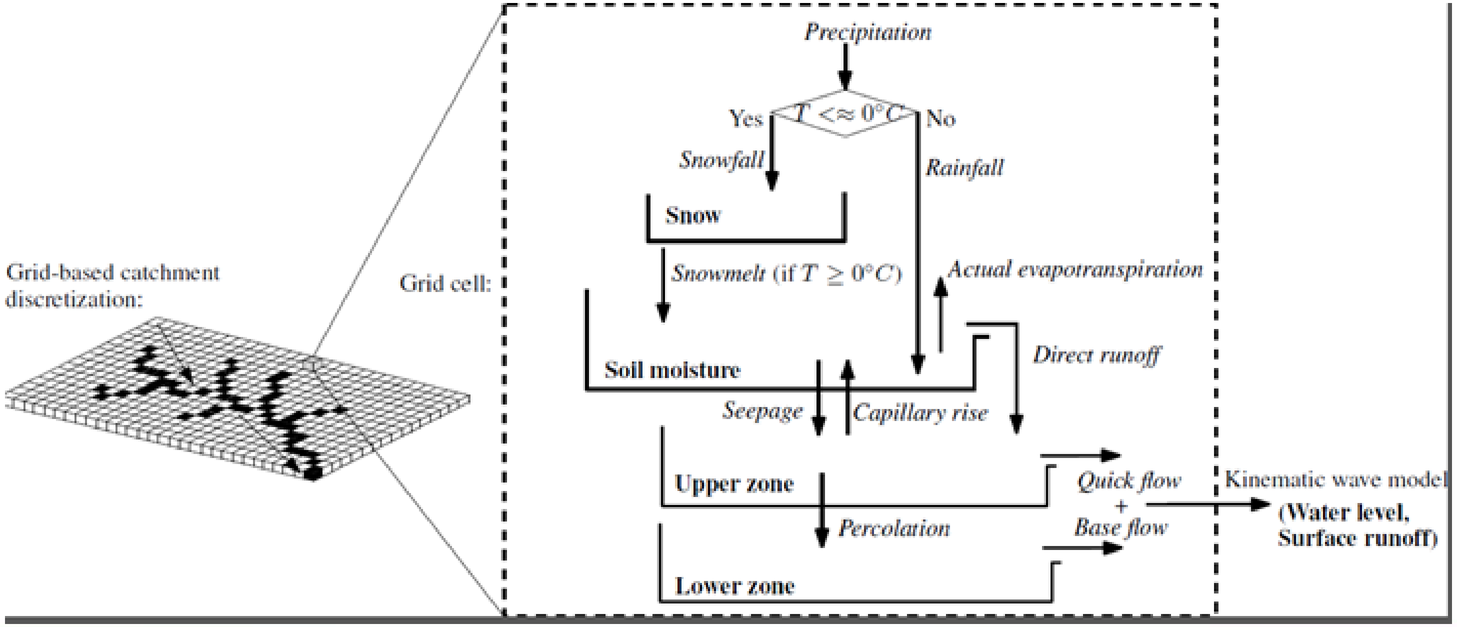
- Why? Lakes matter…





Assimilating waterlevels of 8 Swiss lakes

- HBV policy model (daily timesteps)
- Synthetic and **real world experiments**



Osnabrugge et al., 2019, submitted to JH

‘Real world experiment’

- Perfect forcing Reforecasts for 2003
- Direct Insertion of lake levels,

vs.

- EnKF on lake level

EnKF settings:

Ensemble members = 32

Perturbation noise (spatial):

$$\sigma_P = 0.5 * \mathrm{P}$$

$$\sigma_T = 2℃$$

Observation noise:

$$\sigma_Q = 0.1 * \mathrm{Q}$$

$$\sigma_H = 0.01m$$

Updated states:

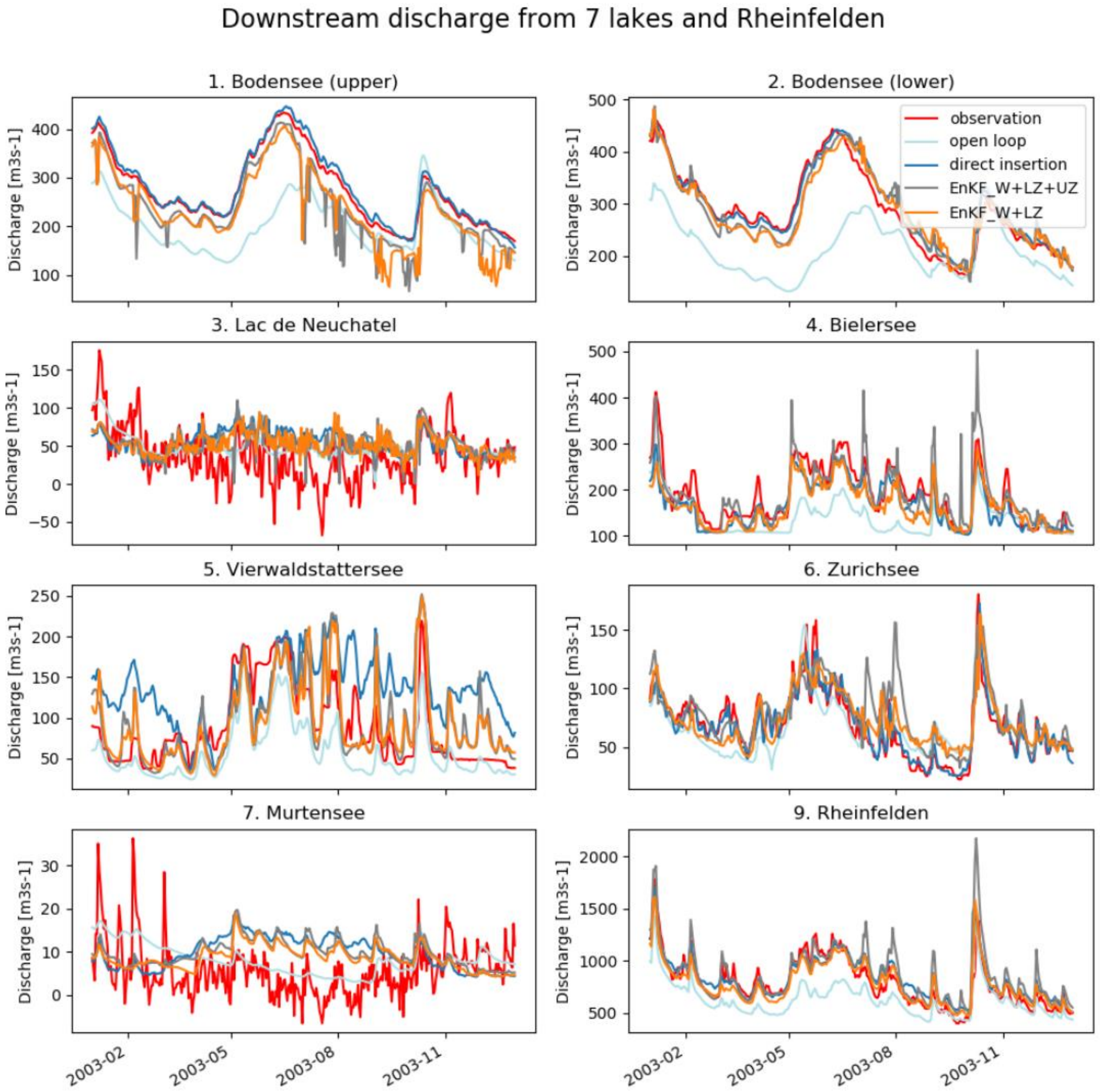
Lake Level

Water level river

(UpperZone)

LowerZone

Historical simulation



Osnabrugge et al., 2019, submitted to JH

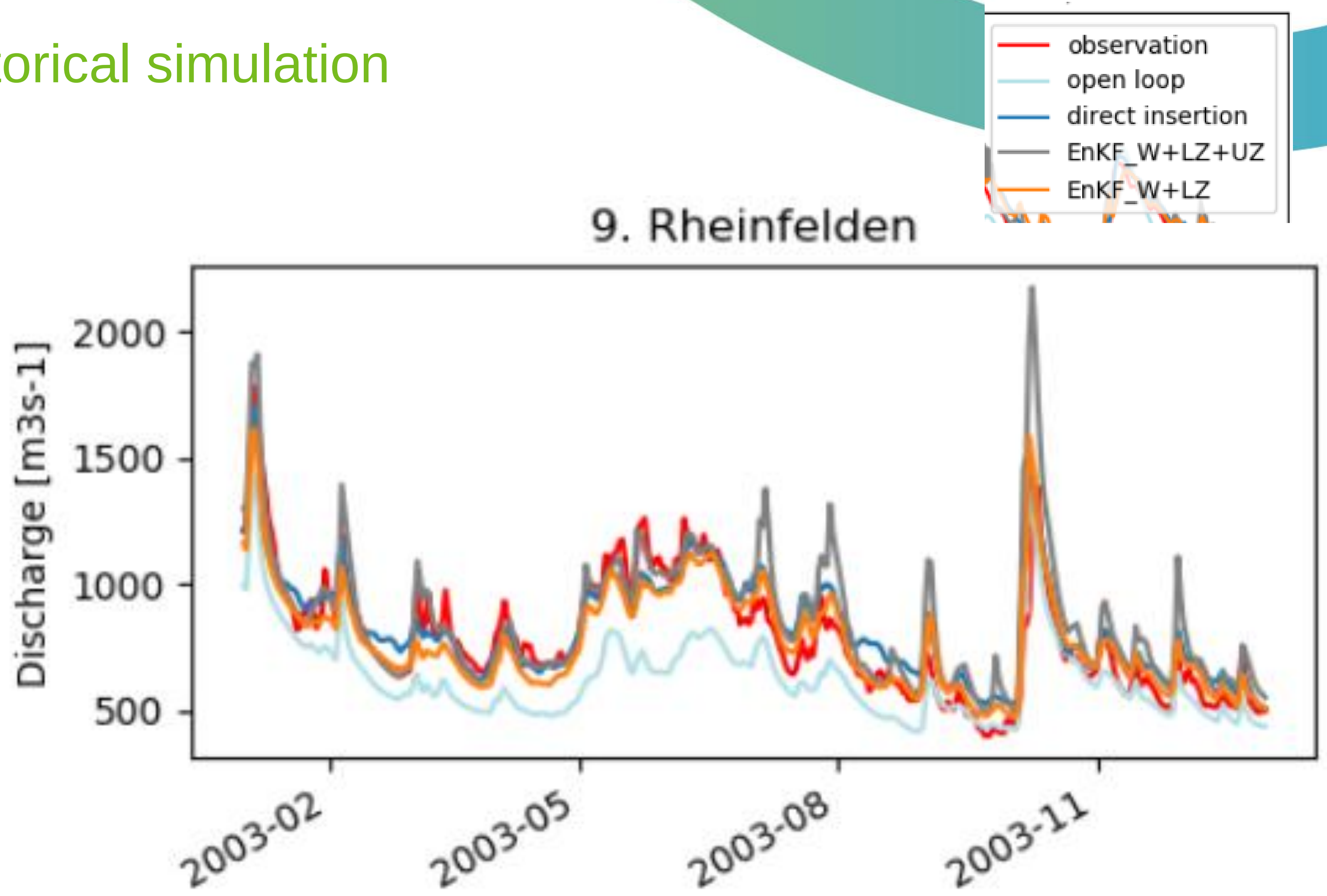
Conclusions historical simulation

- Lake levels contain information about hydrological states upstream

- Updating the upper zone leads to overestimated peak flows in dry times…
  …assimilating only the lower zone store is more robust

- Direct insertion is viable alternative to EnKF
- Lake outflow simulation often needs improvement

Historical simulation

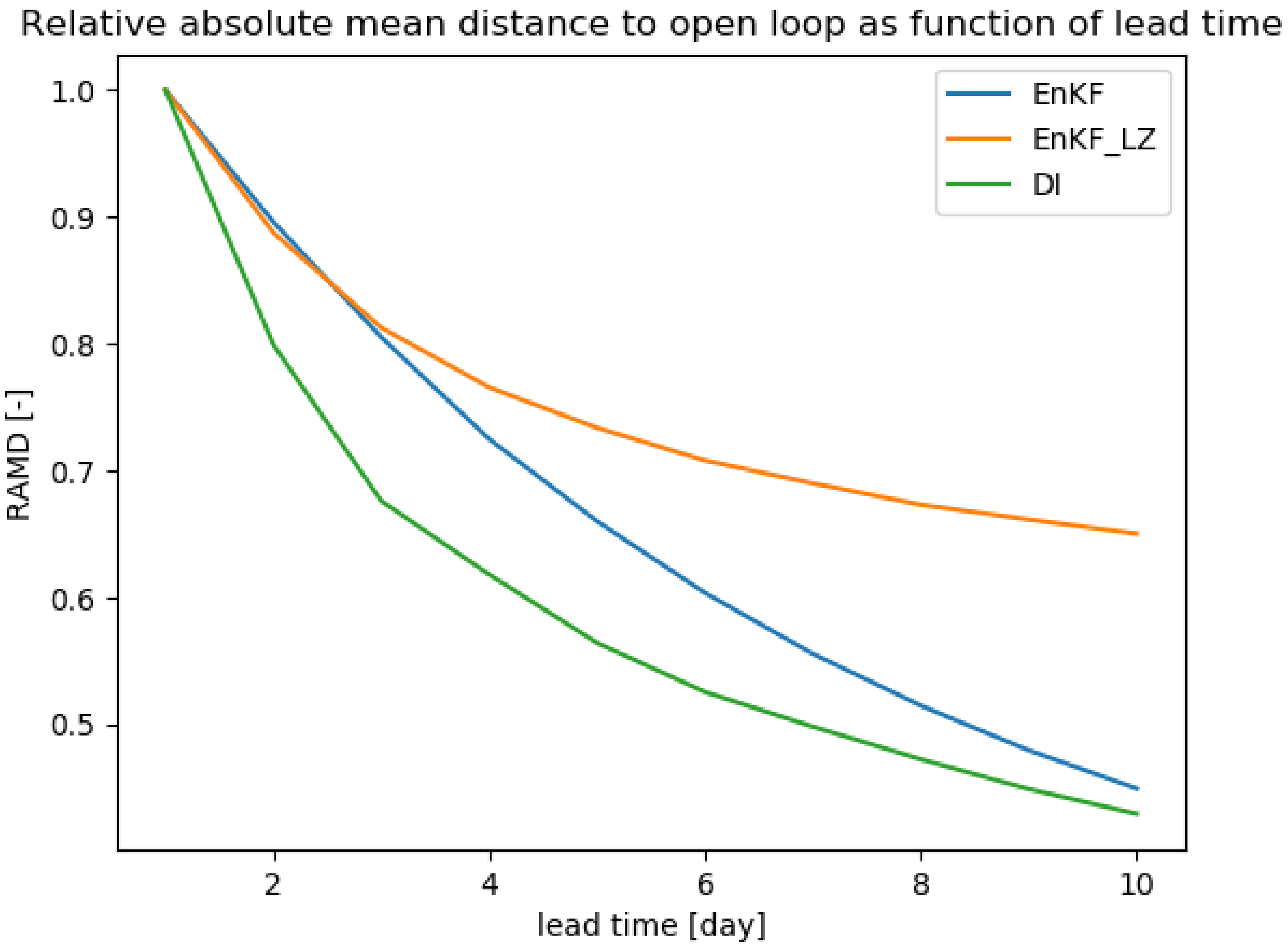


Osnabrugge et al., 2019, submitted to JH

Forecasting at Rheinfelden

- DA has longer memory than DI

→updating hydrological states has potential



Conclusions ‘real world experiment’

Assimilating lake levels is useful but …

… requires more attention to the lake models …

… and…

… more attention to assimilation set up

Basin wide study on DA

- Wflow_hbv model with Rhine clipped into 12 subbasins:

Ahr	Main	Rhine above Maxau
Erft	Mosel	Ruhr
Lahn	Nahe	Sieg
Lippe	Neckar	Wupper

- Timestep is 1 hour, but with parameters derived from policy model
- Historical simulation with GenRE P (van Osnabrugge et al., 2017, WRR), and T and PET grids (van Osnabrugge et al., 2019, HESS)
- Forecasts with ECMWF-ENS reforecasts, 10 members
- Period 1998 – 2015 (excl. 1.5 year warm up)

Data assimilation

- Main German tributaries:
  - Asynchronous EnKF at 6 hour intervals (32 members)
  - perturb P and T, and update Q, H, LowerZone and UpperZone
  - No finetuning, just the settings of Rakovec et al., 2015
- Rhein above Maxau
  - Direct Insertion of lake levels in the 8 largest lakes
- Forecasts depart from mean states, every 3 to 4 days

Osnabrugge et al., in prep. (HESS, 2020)

Results – historical analysis

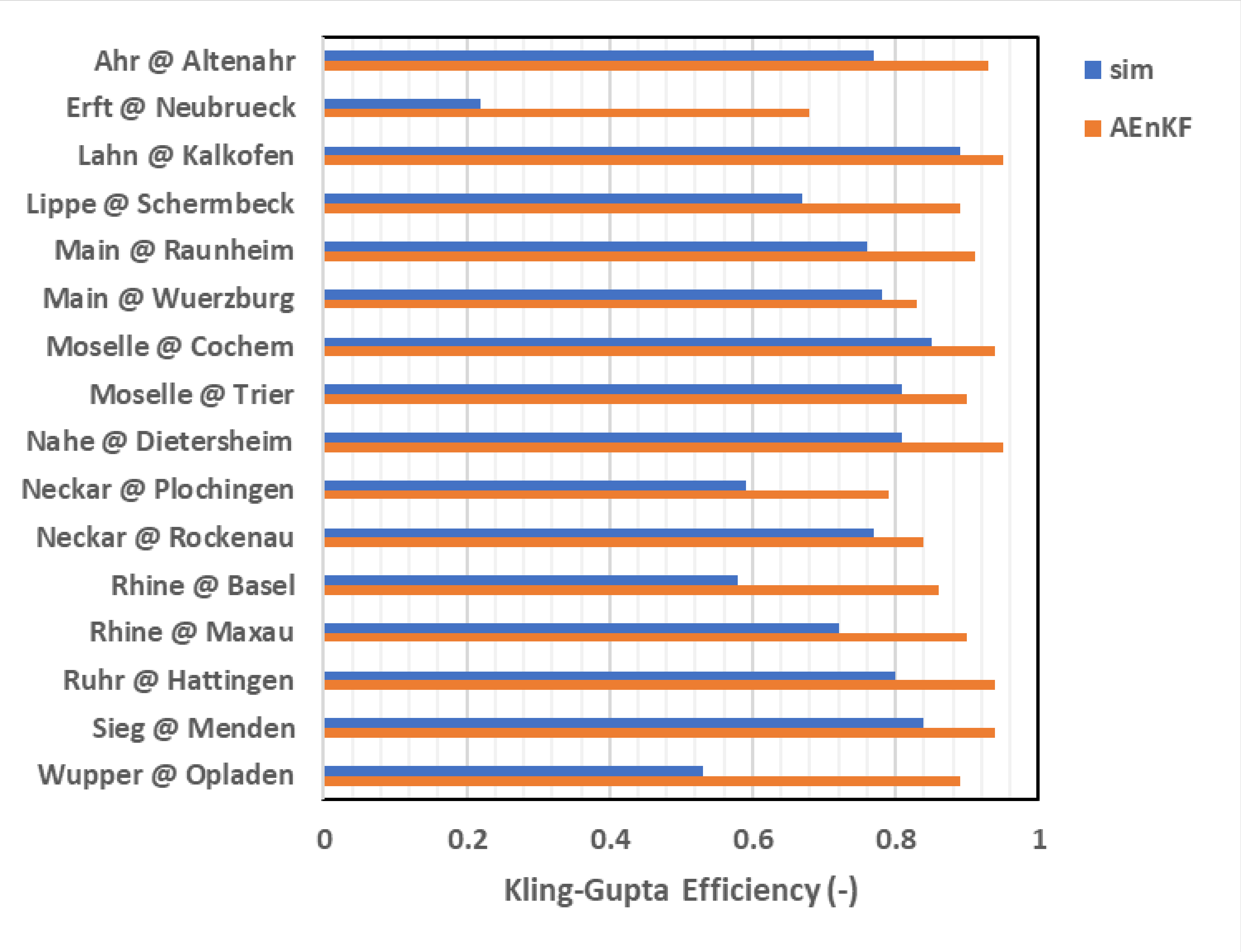
- Model performs allright, or even good…

…except for Erft basin

- Data assimilation is beneficial…

…particularly when the model skill is low

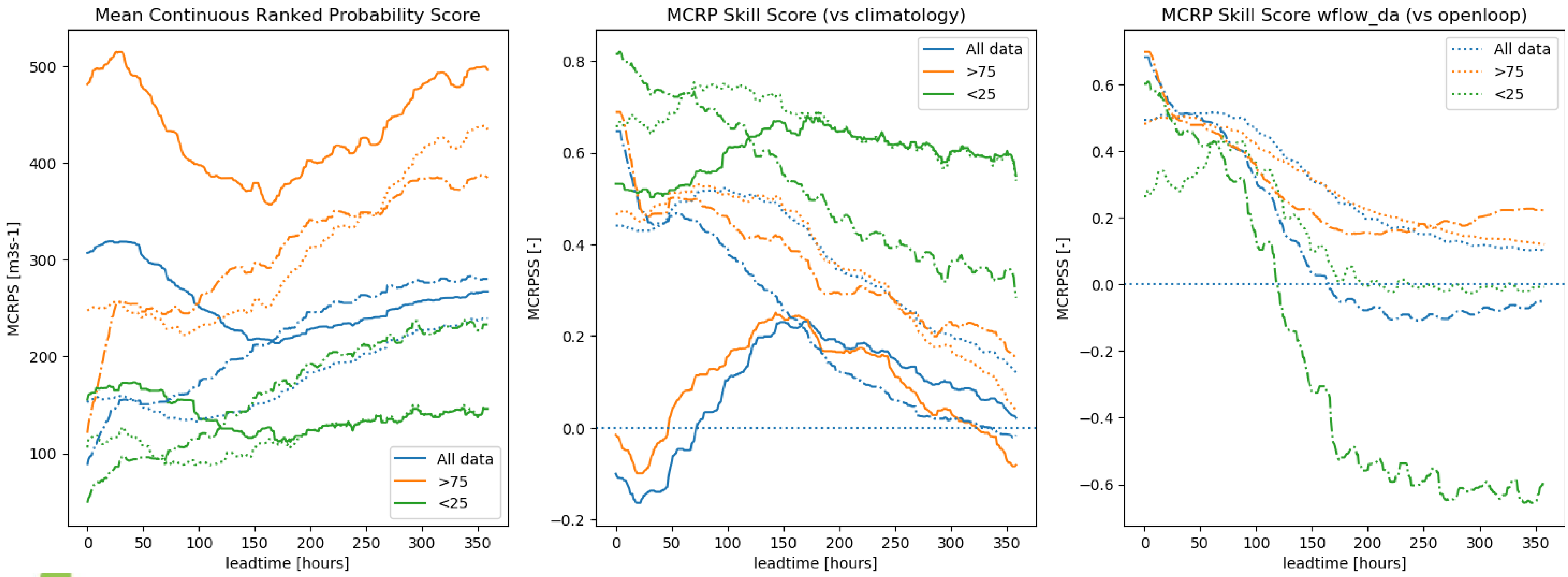
- All large subbasins have KGE scores well above 0.8



Osnabrugge et al., in prep. (HESS, 2020)

Forecasting with DA - Rhine above Maxau

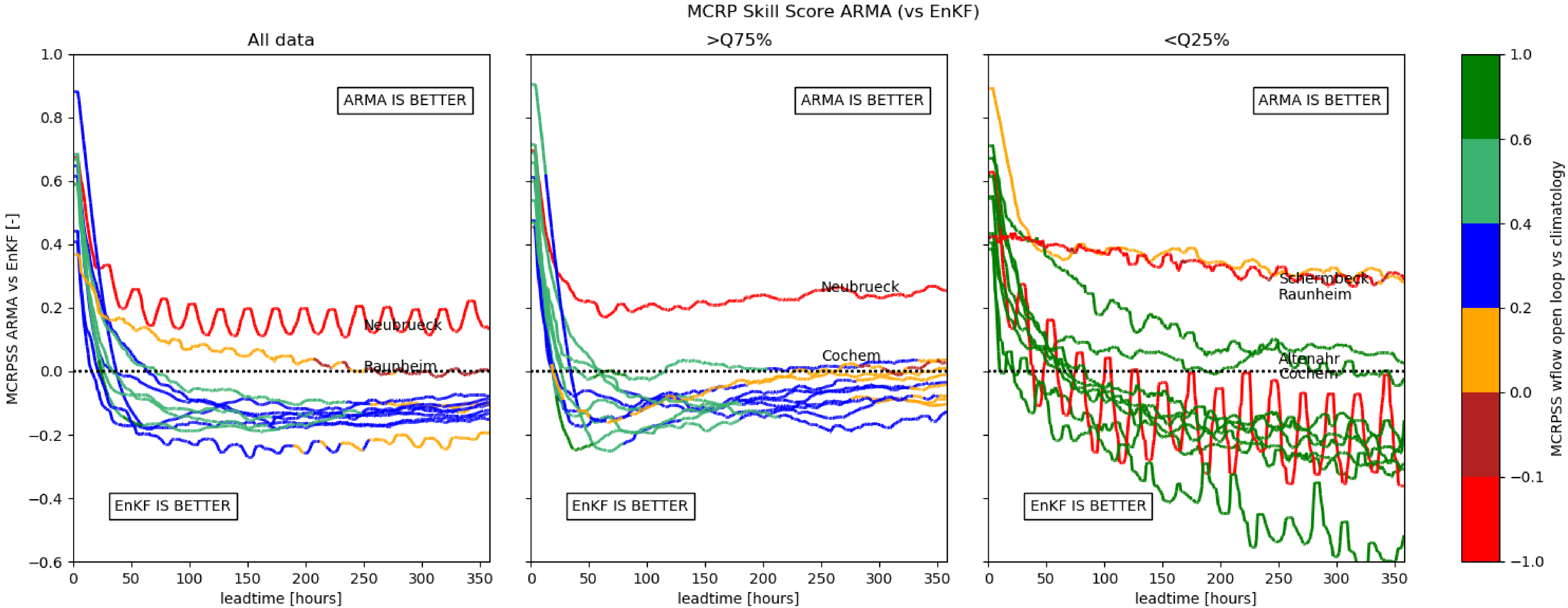
continuous line: HBV
dash-dotted line: HBV + ARMA
dotted line: HBV + DA



Osnabrugge et al., in prep. (HESS, 2020)

Overview all subbasin

- DA usually outperforms ARMA for longer lead times



Osnabrugge et al., in prep. (HESS, 2020)

Winners at longer lead times

winners at longer leadtimes	all flows				>Q75				<Q25				low flows	high flows
	climate	HBV	HBV + ARMA	HBV + DA	climate	HBV	HBV + ARMA	HBV + DA	climate	HBV	HBV + ARMA	HBV + DA		
Ahr				1				1			0.5	0.5	1	
Erft	1				1							1	1	
Lahn				1				1				1	1	
Lippe				1		1					1		1	
Main			0.5	0.5		1					1		1	
Moselle		0.5		0.5		0.33	0.33	0.33		1			1	
Nahe				1				1				1	1	
Neckar				1				1				1	1	
Rhine @ Maxau				1			0.5	0.5		1				1
Ruhr				1		1						1	1	
Sieg			0.5	0.5			0.5	0.5				1	1	
Wupper				1				1				1	1	
TOTAL	**1**	**0.5**	**1**	**9.5**	**1**	**3.33**	**1.33**	**6.33**	**0**	**2**	**2.5**	**7.5**	**11**	**1**

Osnabrugge et al., in prep. (HESS, 2020)

Conclusions

- Seamless distributed parameter maps can be obtained for the gridded hydrologic model wflow_sbm with transfer-functions from literature.
- Application of wflow_sbm with these seamless parameter maps yield simulation results with high KGE and NSE across the Rhine basin.
- Fluxes matched across model scales for evapotranspiration, but this match less for fluxes affected by (sub)surface flows.
- We developed a distributed hydrological model ready for data assimilation of HSAF or oter project (IMPREX-HSAF testbed)
- There is a negative bias in the precipitation data over the swiss Alps
- DA assimilation of waterlevels of Swiss lakes either with Direct Insertion or EnKF yield considerable better forecasts
- Modelling of lakes may need more attention
- Streamflow data assimilation for most Rhine tributaries beneficial
- Ensemble DA outperformance ARMA error correction for longer leadtimes and vice versa for shorter leadtimes

Work underway in collab with Ewatercycle II

- Enable joint assimilation of point streamflow and gridded surface soil moisture observation using the distributed hydrological model wflow_sbm model for the Rhine developed within H2020 IMPREX.

- OpenDA (and wflow) was extended to enable local analysis to make this possible (conducted with Ewatercycle II)

- This will be tested also as part of the HEPEX-HASF testbed for the Lahn (ongoing)

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References

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-Van Osnabrugge, R. Uijlenhoet, A.H. Weerts, 2019. Contribution of potential evaporation forecasts to 10-day streamflow forecast skill for the Rhine River. HESS (https://www.hydrol-earth-syst-sci.net/23/1453/2019/)

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-Van Osnabrugge, B., R. Uijlenhoet, A.H. Weerts, 2019. Assimilation of multiple lake levels in an operational integrated catchment model of the Swiss Rhine basin. Submitted to Journal of Hydrology X.

-Van Osnabrugge , B., M. Smoorenburg, R. Uijlenhoet , A.H. Weerts, 2019. Large scale data assimilation for the Rhine tributaries: assessment of skill using NWP reforecasts, to be submitted to HESS.

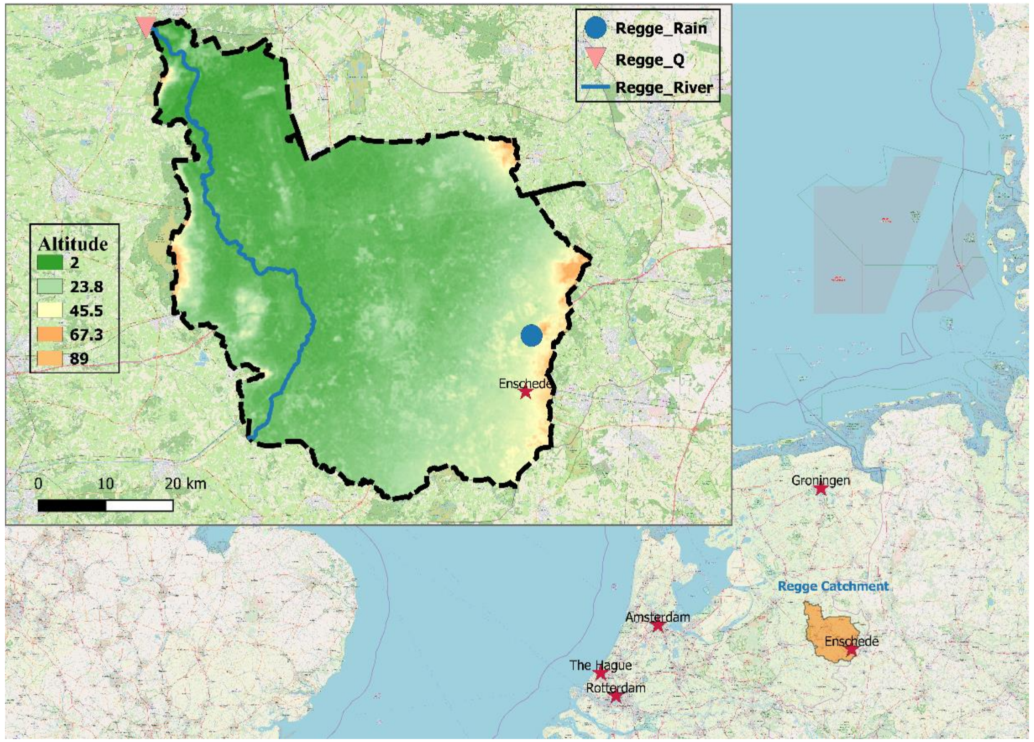
Datasets

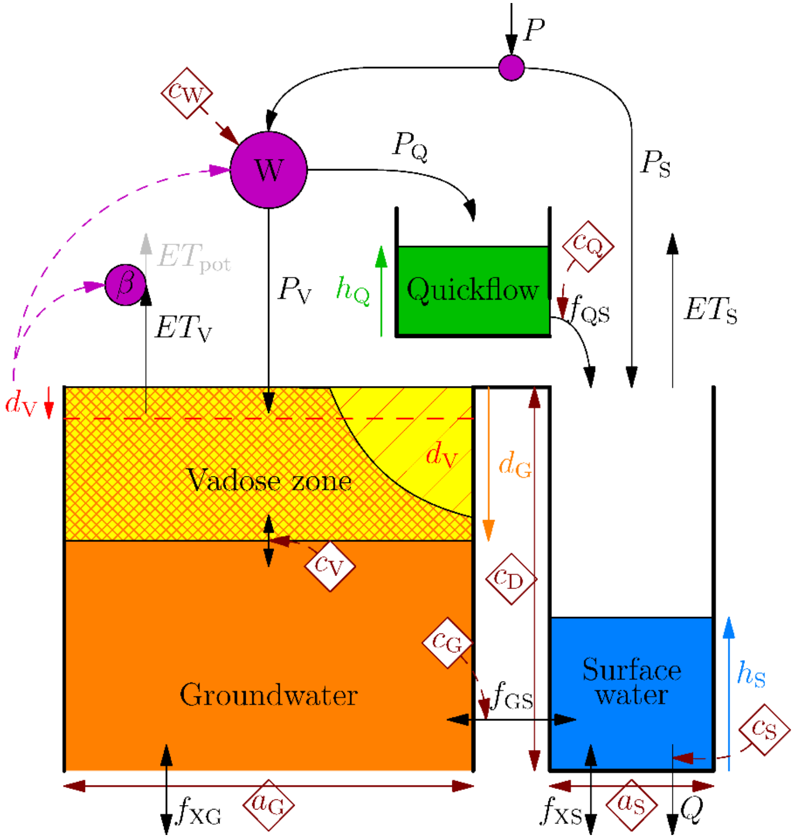
-Osnabrugge, B. van, R. Uijlenhoet, A.H. Weerts, 2017. Gridded precipitation dataset for the Rhine basin made with the genRE interpolation method https://data.4tu.nl/repository/uuid:c875b385-ef6d-45a5-a6d3-d5fe5e3f525d.

-Osnaburgge, B. van, A.H. Weerts, 2018. Gridded Hourly Temperature, Radiation and Makkink Potential Evaporation forcing for hydrological modelling in the Rhine basin https://data.4tu.nl/repository/uuid:e036030f-c73b-4e7b-9bd4-eebc899b5a13.

Lumped models continued (& algorithms)

- However when routing/delay doesn't play a big role DA can work quite nicely





Sun et al., 2019 (submitted to WRR)

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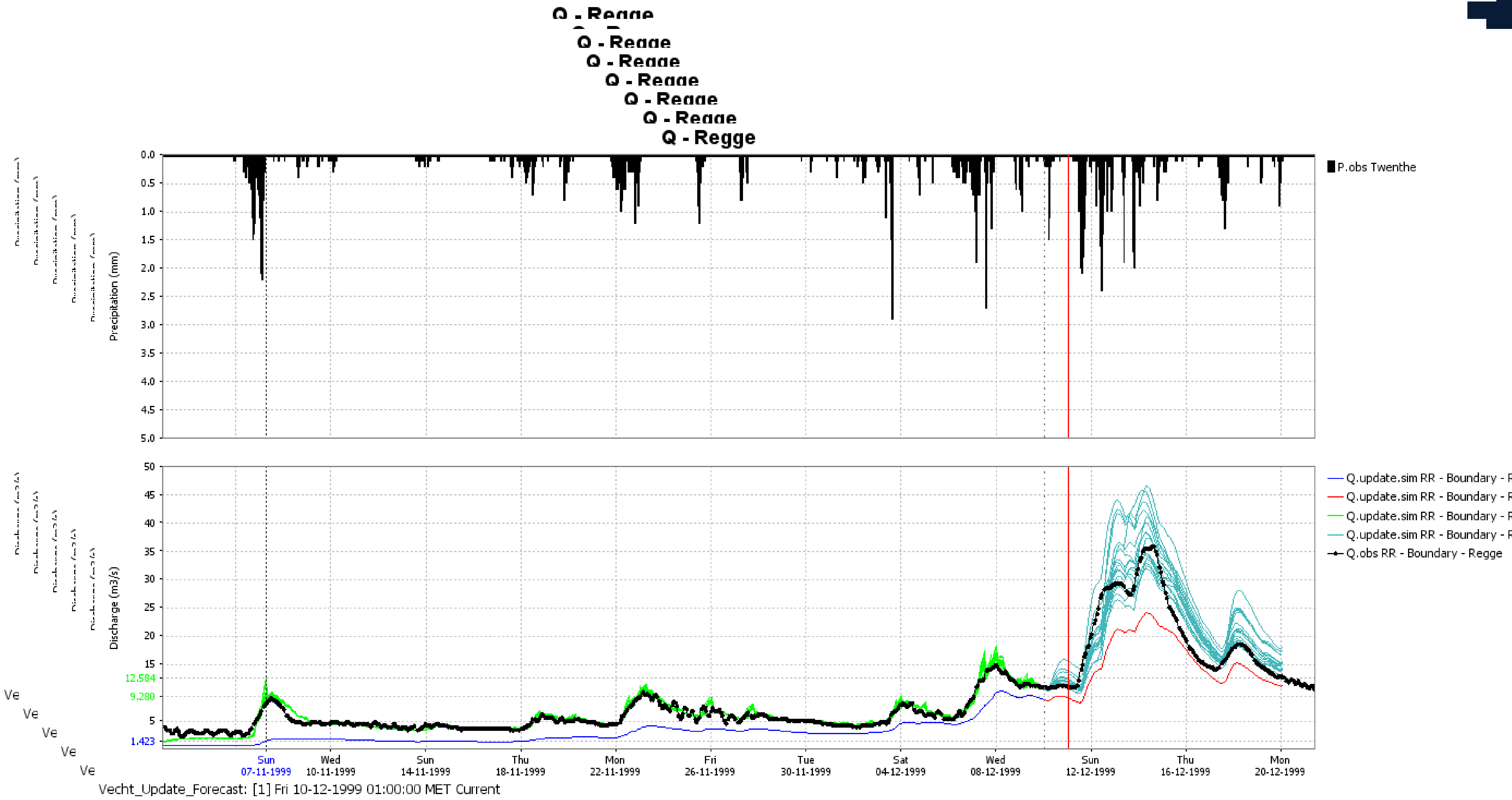
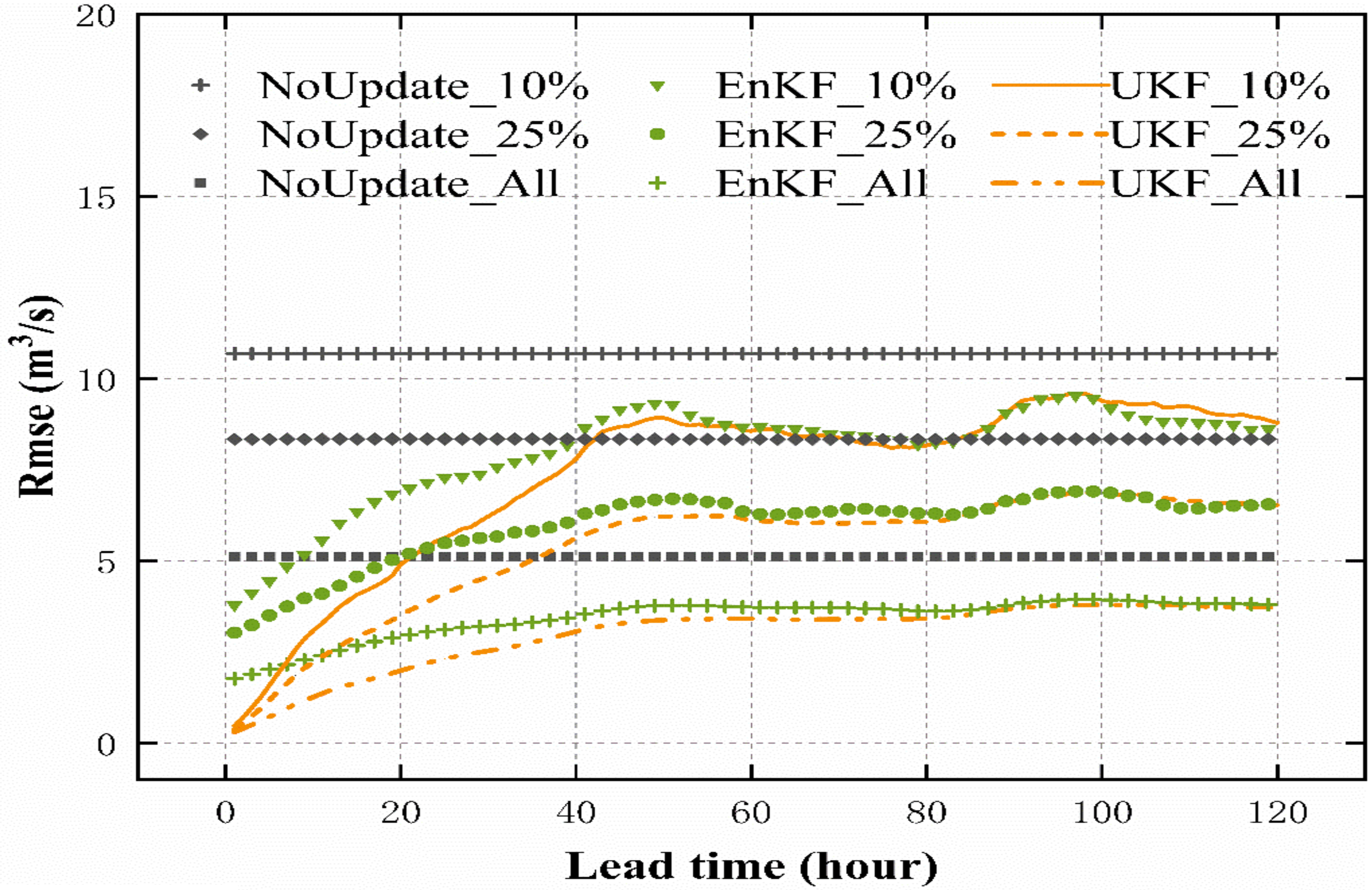

Q - Regge
Precipitation (mm)
P.obs Twenthe
Discharge (m3/s)
Q.update.sim RR - Boundary - R
Q.update.sim RR - Boundary - R
Q.update.sim RR - Boundary - R
Q.update.sim RR - Boundary - R
Q.obs RR - Boundary - Regge
12.584
9.280
1.423
Sun 07-11-1999
Wed 10-11-1999
Sun 14-11-1999
Thu 18-11-1999
Mon 22-11-1999
Fri 26-11-1999
Tue 30-11-1999
Sat 04-12-1999
Wed 08-12-1999
Sun 12-12-1999
Thu 16-12-1999
Mon 20-12-1999
Vecht_Update_Forecast: [1] Fri 10-12-1999 01:00:00 MET Current

Lumped models continued (& algorithms) III



Sun et al., 2019 (submitted to WRR)

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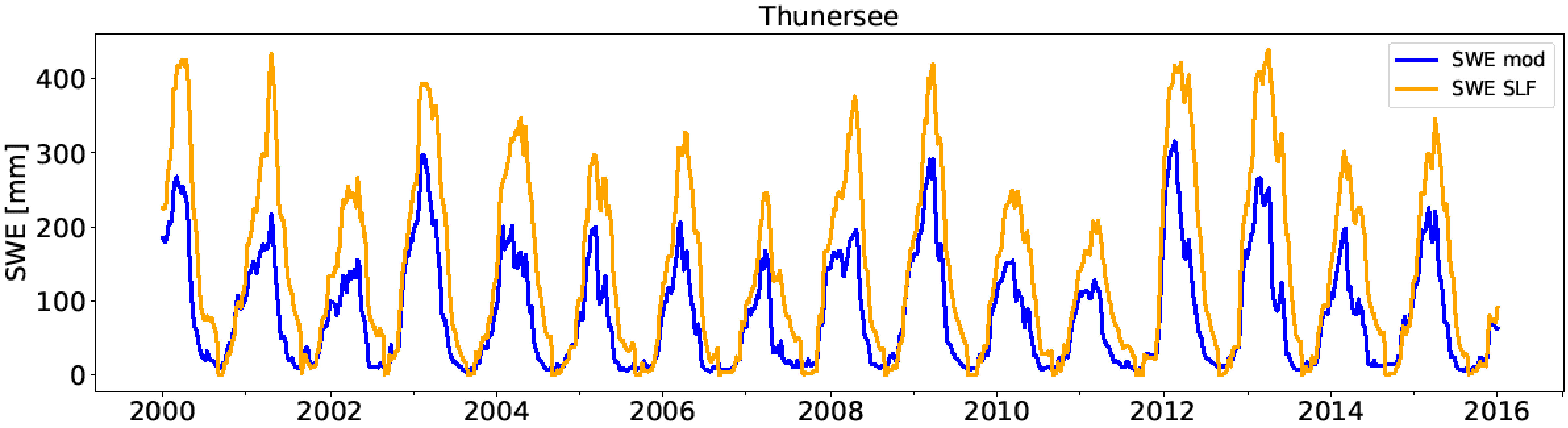
Deltares

Modelled SWE Thunersee (wflow_sbm and SLF)



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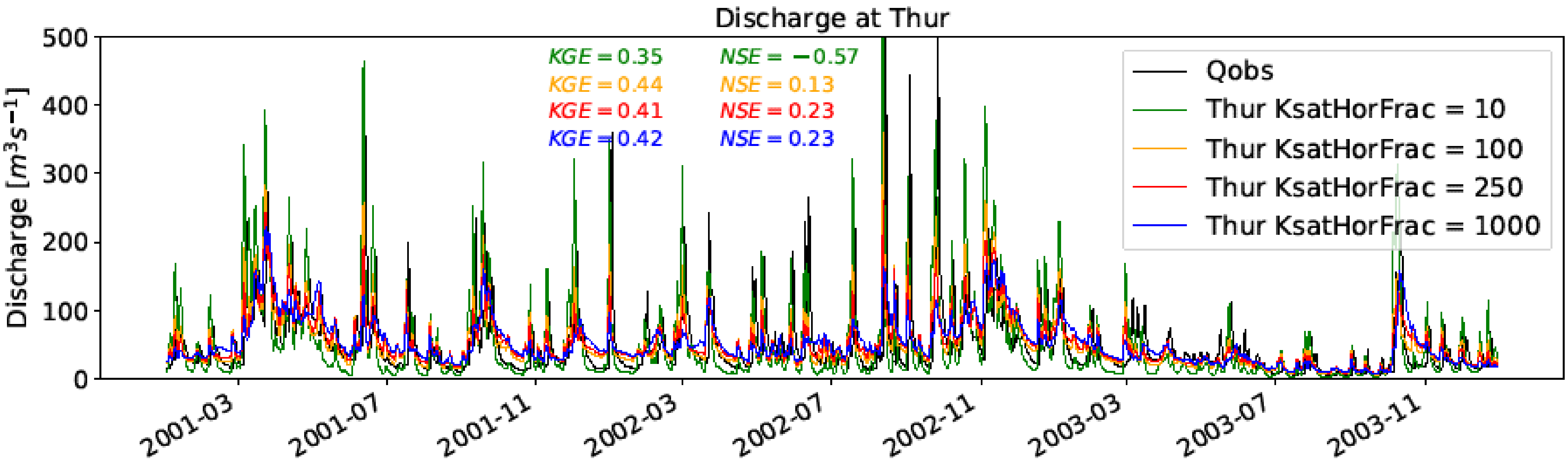
Performance as function of ksathorfrac



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Comparison wflow_sbm versus wflow_hbv and mHM