Deltares
Enabling Delta Life

WAGENINGEN UNIVERSITY
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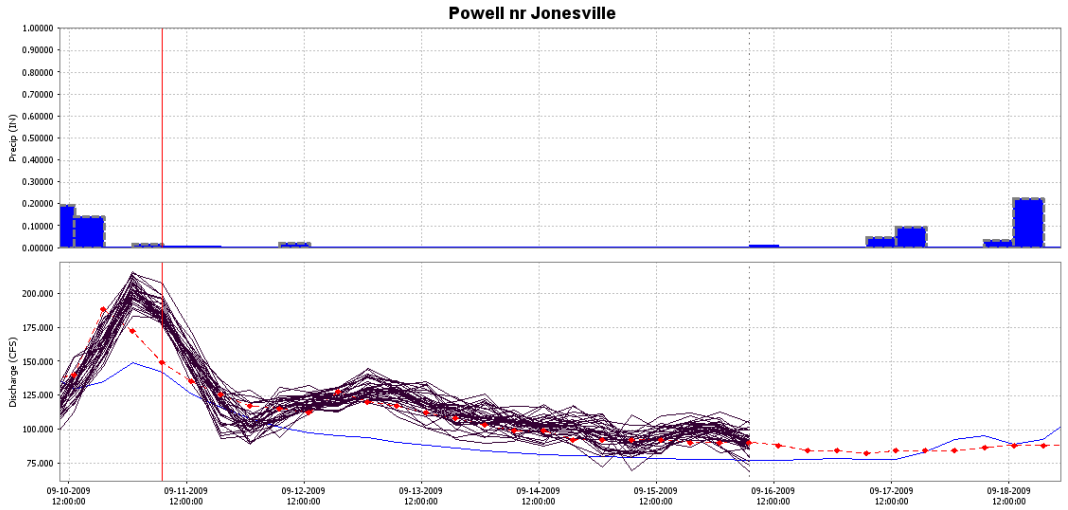
Towards operationalizing ensemble DA in hydrologic forecasting

Albrecht Weerts

5-7 November HEPEX



What provides hydrologic forecast skill?

Boundary Conditions (A)

NWP

-EPS

-high resolution

Initial conditions (C)

Data assimilation

- manual

- automatic methods

Quality hydrologic/hydraulic model (or model chain) (B)

Model calibration

Resolution, parameterization etc

Statistical post processing (D)

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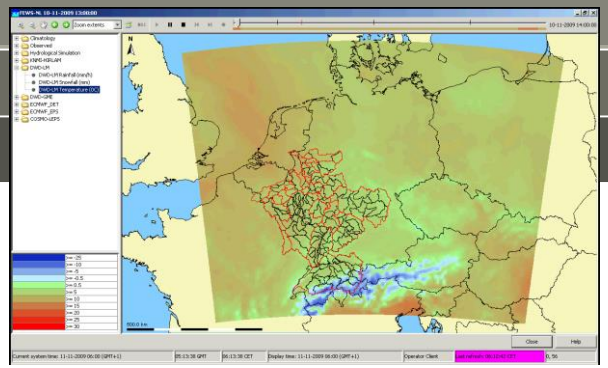
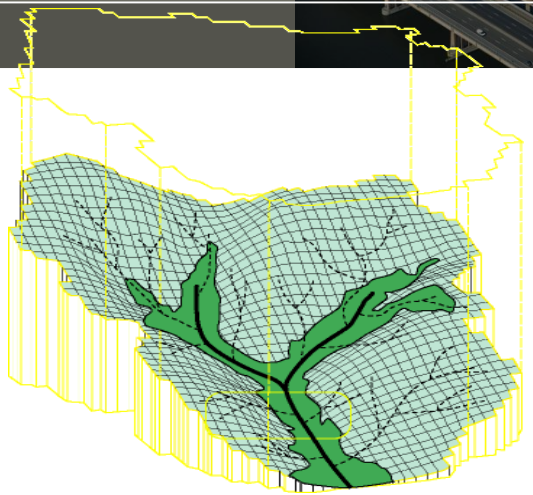




meteorological model B + C
model & initialization error

A

New measurements

rainfall runoff model B + C
model & initialization error

D

routing model B + C
model & initialization error

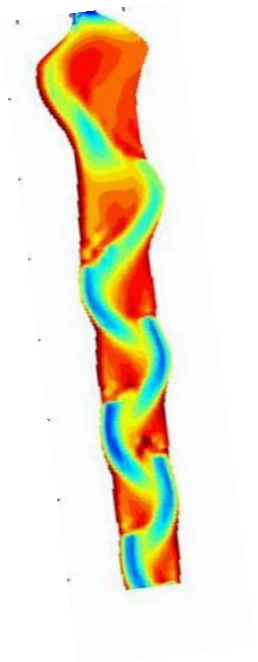
D

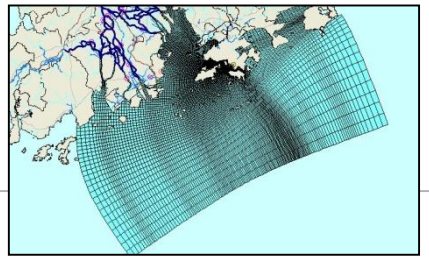
hydrodynamical model B + C
model & initialization error

D

storm surge model B + C
model & initialization error

Model Calibration





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What is data assimilation

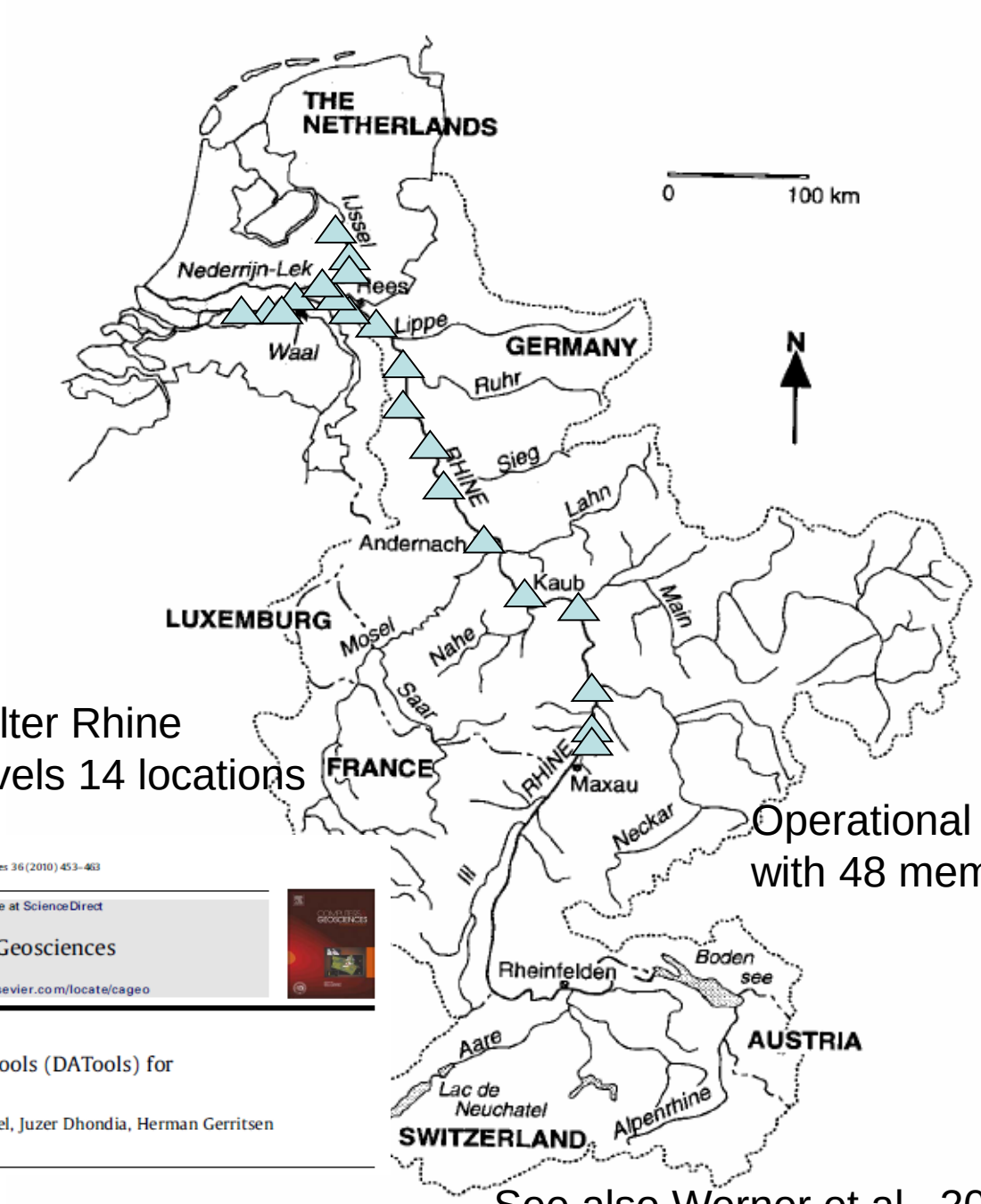
Generic model formulation

$$\frac{dx}{dt} = M[x(t), u(t), p, w(t)]$$

State: $x(t)$ — Parameters: p — Forcings: $u(t)$ — Noise: $w(t)$

Improve the model outcome by applying systematic perturbations to [*x*,*u*,*p*,*w*]

Optimization through knowledge of model uncertainty (multiple instances)
What is systematic? DA method
What is the reference? observations + observation error/uncertainty



Ensemble Kalman Filter Rhine assimilation water levels 14 locations

Operational since 1-1-2008 with 48 members

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journal homepage: www.elsevier.com/locate/cageo

Application of generic data assimilation tools (DATools) for flood forecasting purposes

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Deltares, P.O. Box 177, 2600 MH, Delft, The Netherlands

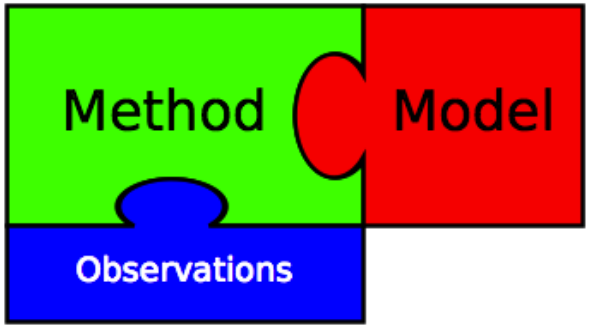
See also Werner et al., 2014

What is OpenDA

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

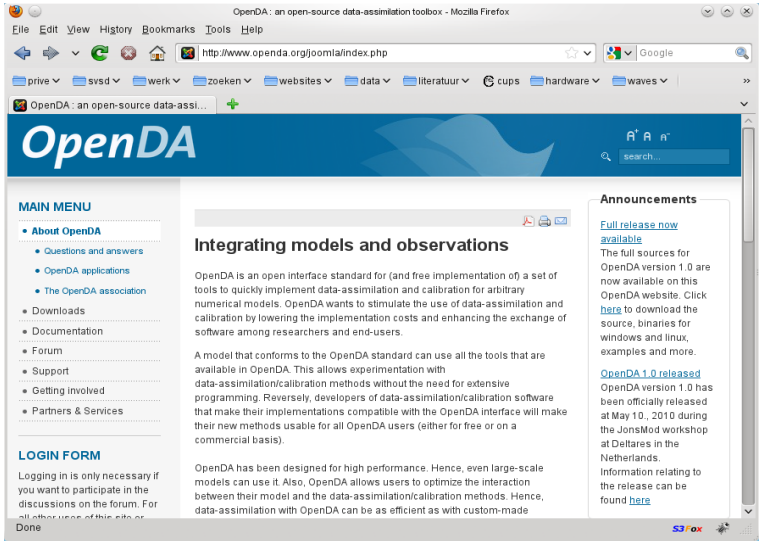
It encompasses:

- An architecture for applying (stochastic) data assimilation algorithms to deterministic models
- A set of interfaces that define interactions between components
- A library of data assimilation, UA and calibration methods:
  - EnKF, EnSR, EnKFD, AENKF, PF-RR, 3DVar, …
  - Dud, Simplex, Powell, Conjugate Gradient, …
  - GLUE, DELSA,…



What is OpenDA

- Open source (LGPL)
- Written in Java / C / Fortran
- Current version: OpenDA 2.1
- Available for Windows, Linux & Mac
- Website: www.openda.org with downloads, documentation, support
- The OpenDA Association:



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OpenDA

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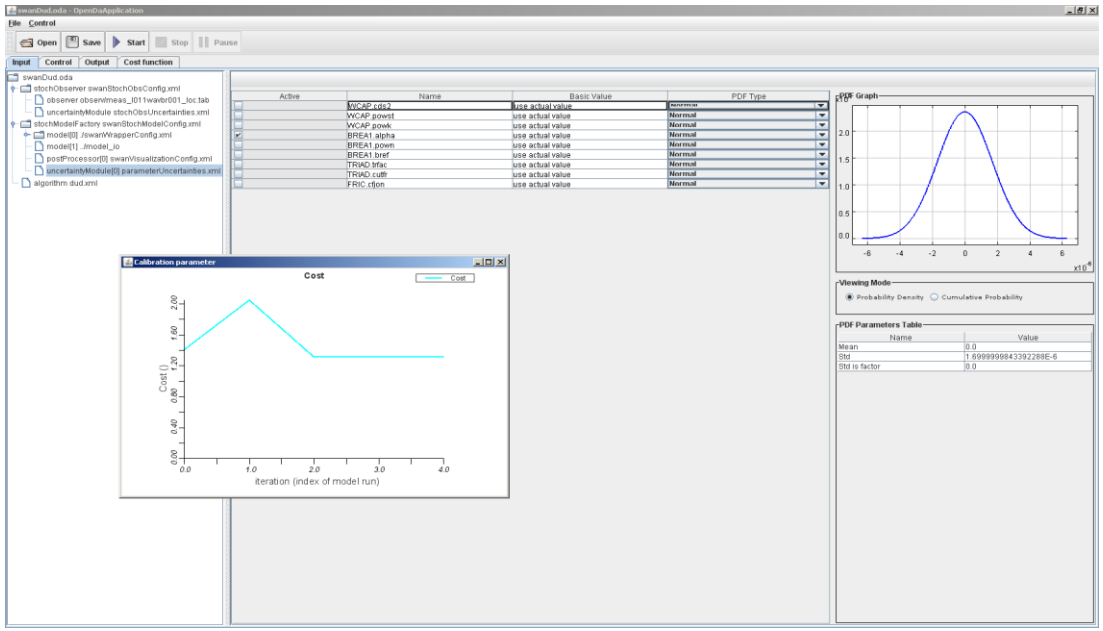
Why OpenDA?

- More efficient than development for individual applications
- Shared knowledge between applications
- Development of algorithms with e.g. universities
- Easier to change algorithm
- Easier to test, which should result in fewer bugs
- Optimized building blocks
- Development template
- Comparing algorithms in one framework!

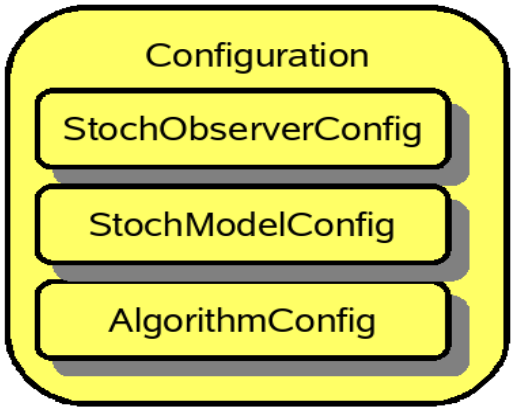
OpenDA Main Application

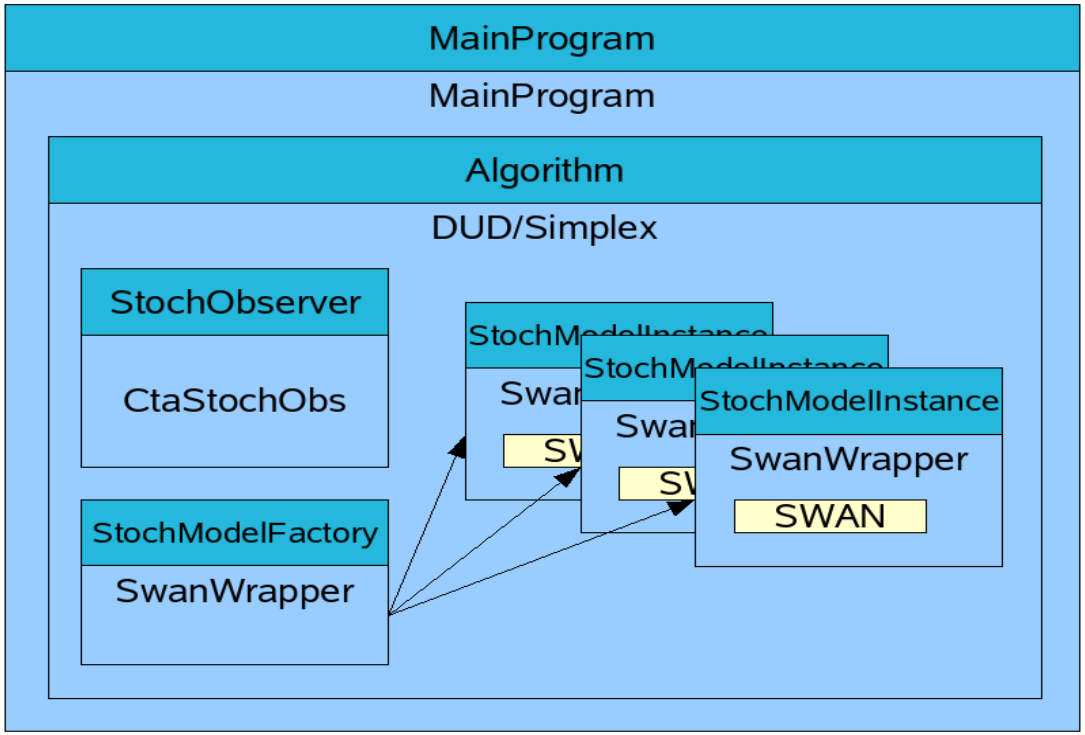
Single program

- GUI and command line
- Multiple configuration files
- Calibration and Filtering
- ‘All’ models
- ‘All’ observation sources
- Sequential and parallel



OpenDA architecture



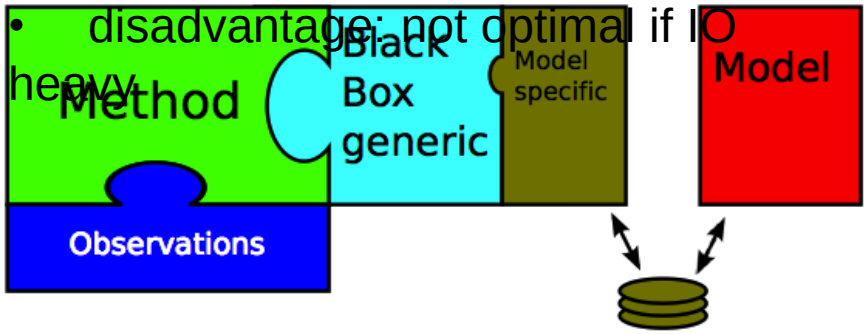


OpenDA

Model coupling: two approaches

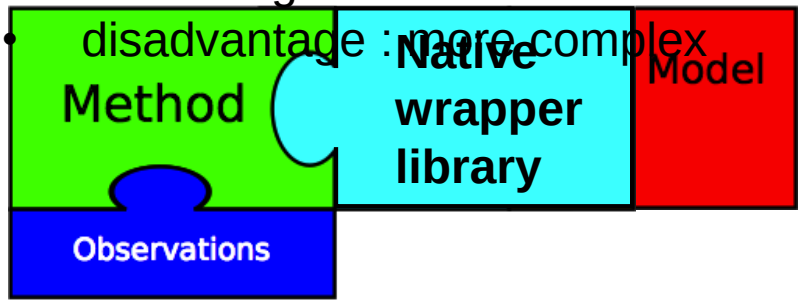
BlackBox coupling:

- model executable (no source required)
- use model input/output files
- $TIME wildcards in configuration
- model requirements:
  - ✓ accurate restart
  - ✓ good documentation of files
  - ✓ run from the command line
- disadvantage: not optimal if IO heavy

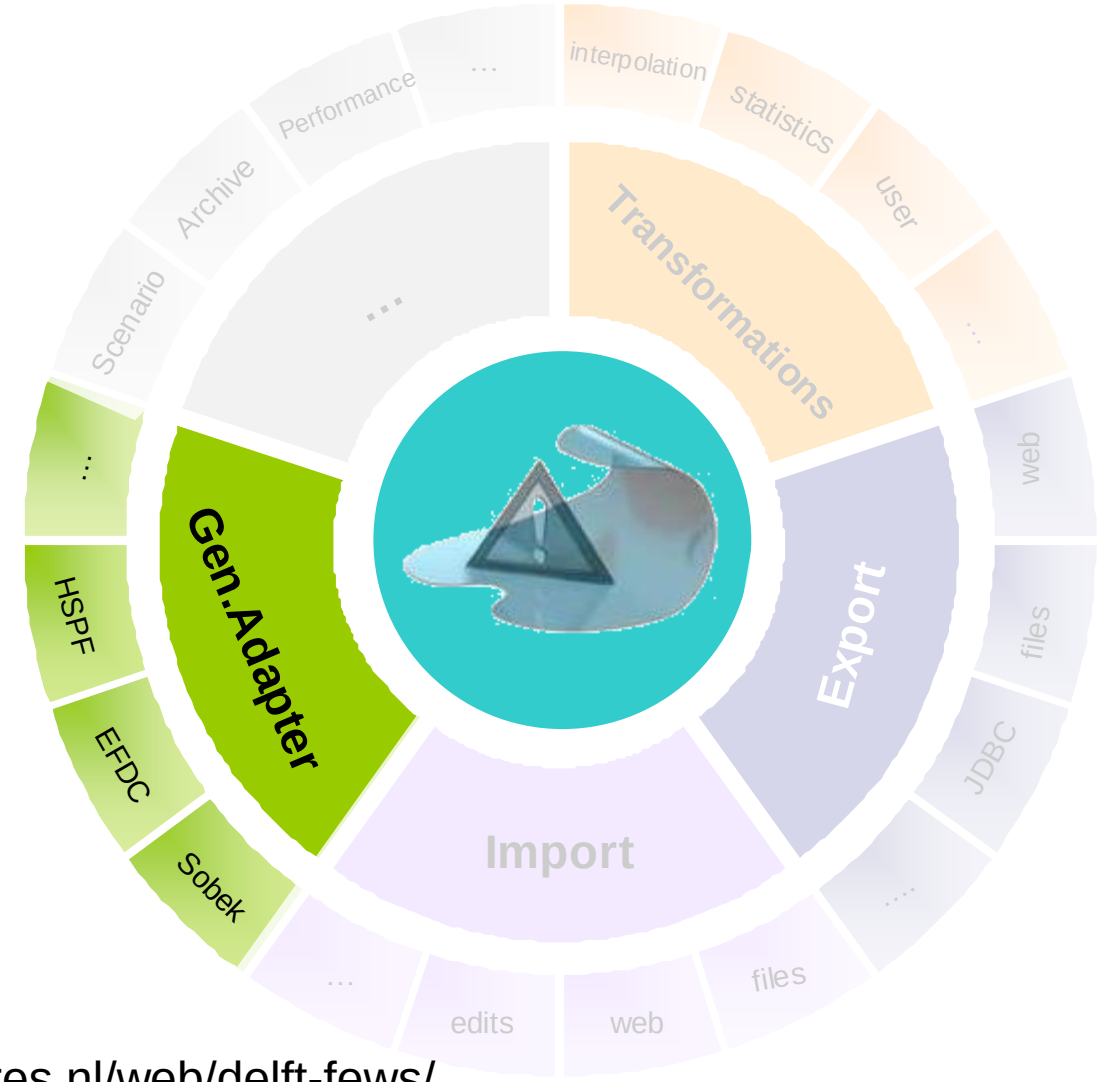


Native model wrapper

- model as a library
- communicate directly with model data objects (double precision arrays)
- model library requirements:
  - ✓ accurate restart (or fix it)
  - ✓ good code documentation
  - ✓ go back in time / instance management / time management
- disadvantage : more complex



Application in of OpenDA in Delft-FEWS



http://oss.deltares.nl/web/delft-fews/

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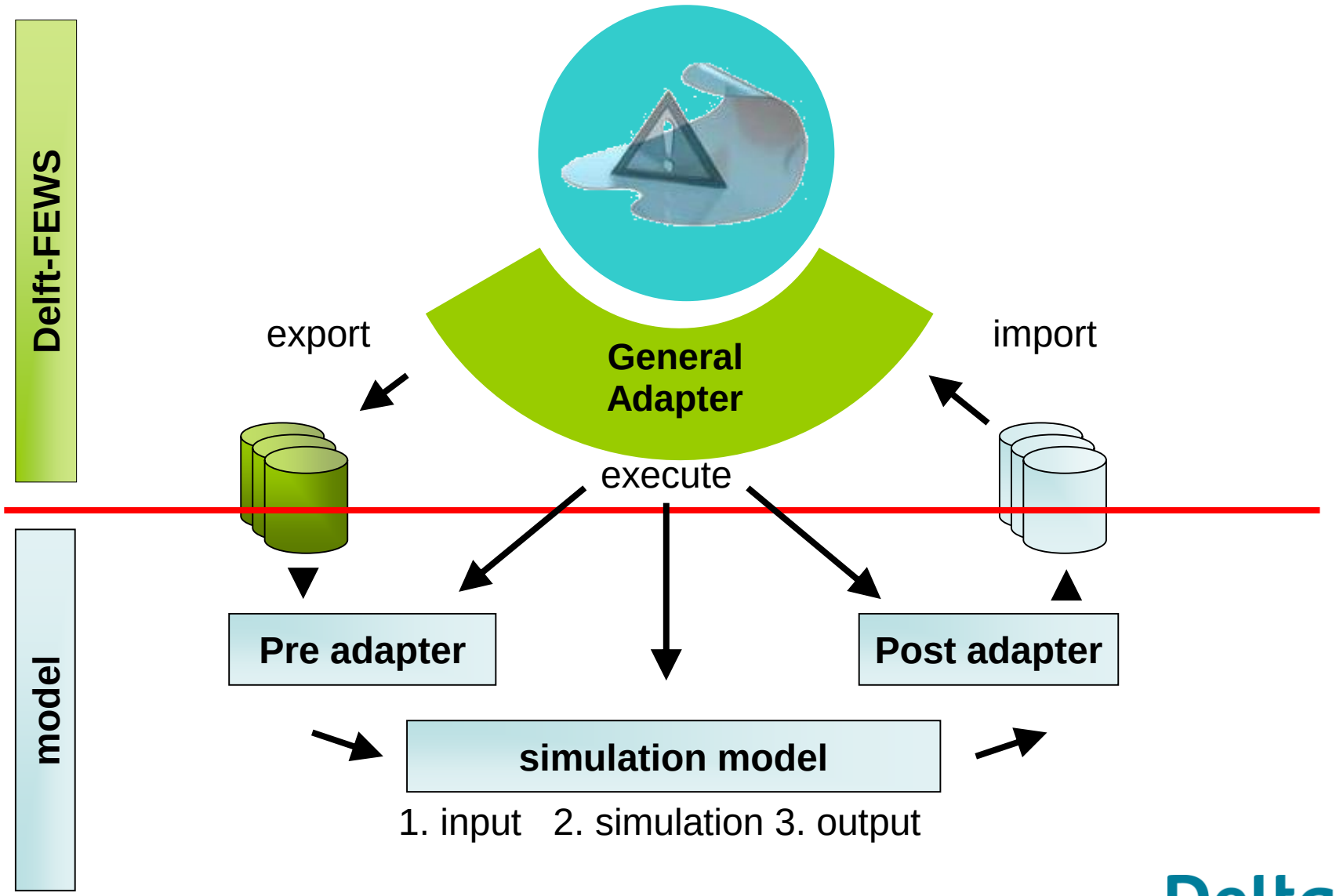
Coupling with models; without OpenDA



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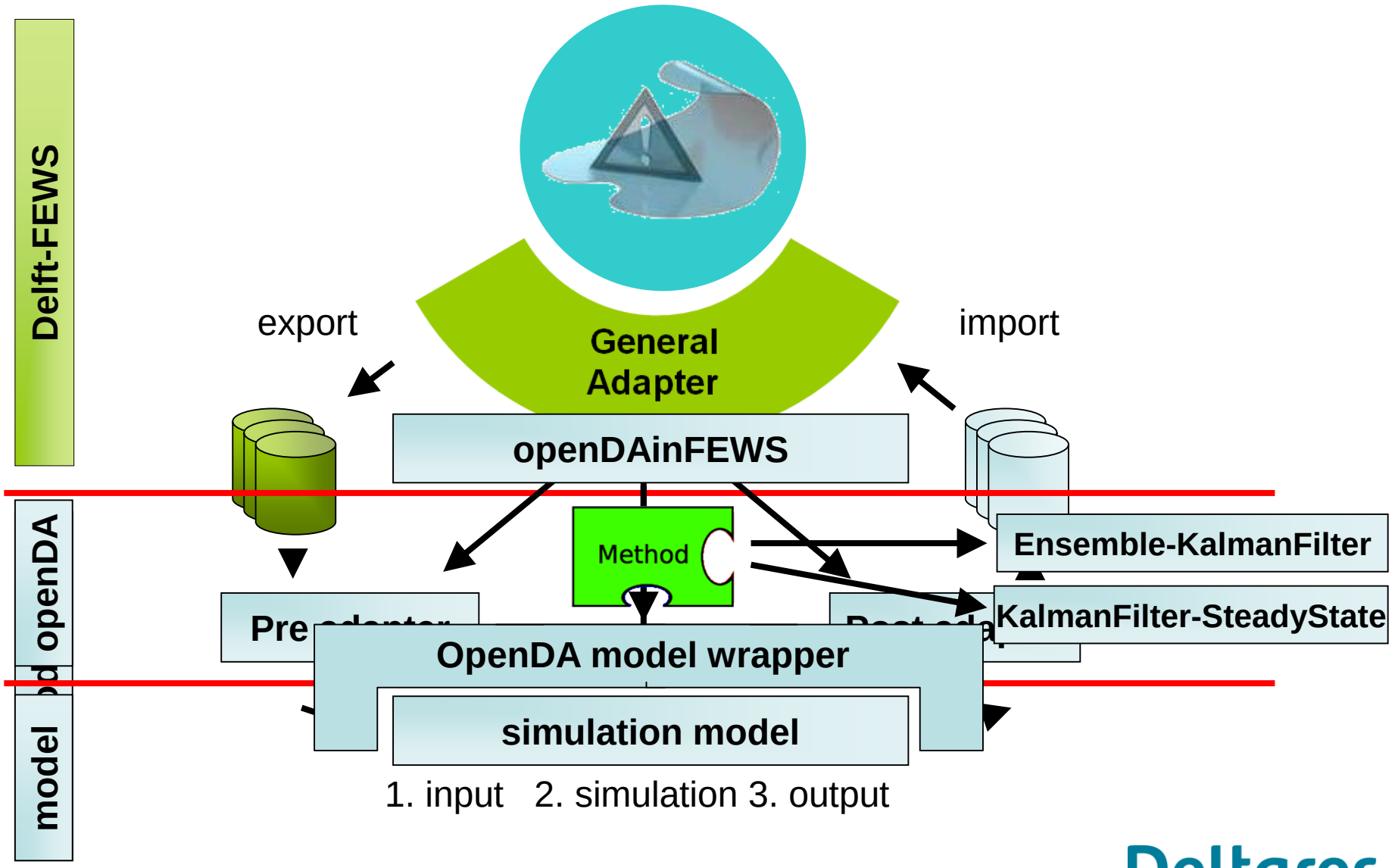
Coupling with models; via OpenDA blackbox



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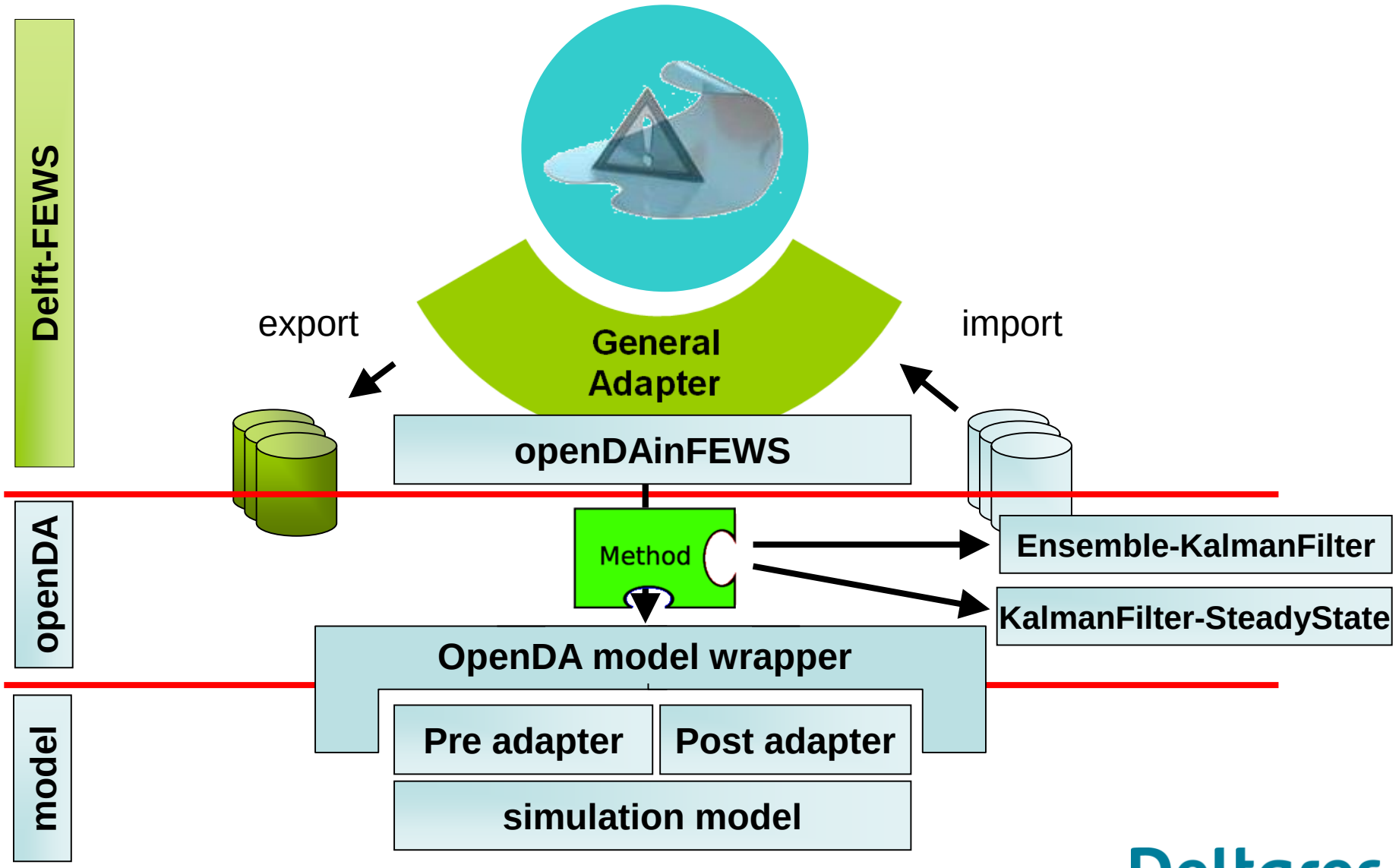
Coupling with models; via openDA dll (in memory)



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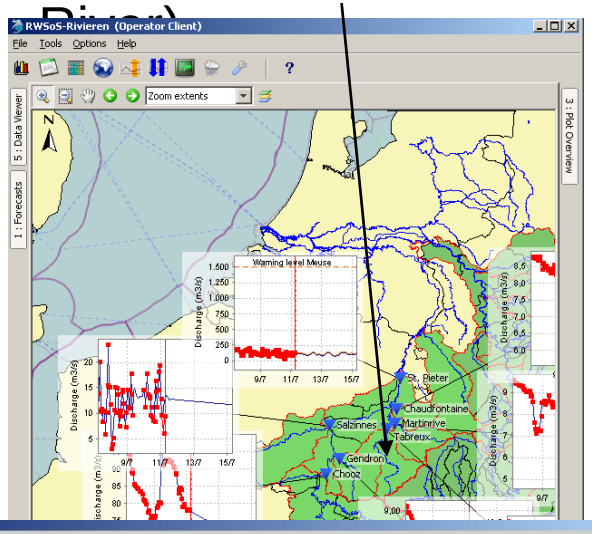
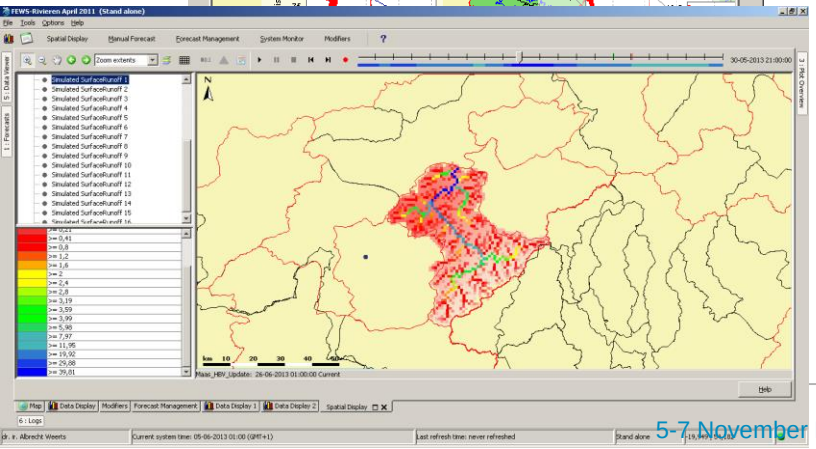
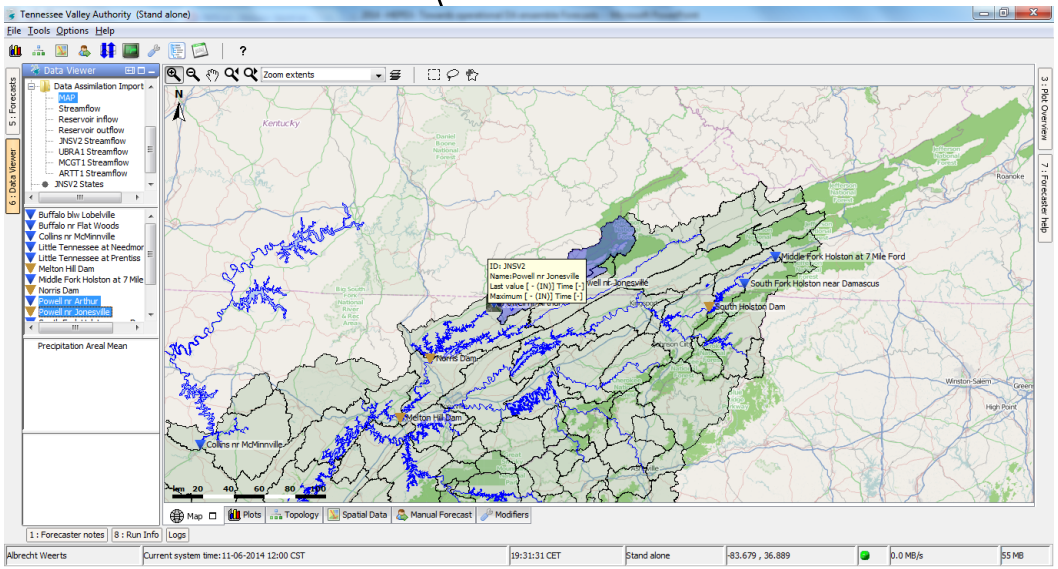
2 examples Delft-FEWS-OpenDA-Model

Open Source OpenStreams
Distributed Hydrologic Model
(Belgium – Ourthe catchment)





Lumped hydrologic model chains
(Tennessee Valley USA)



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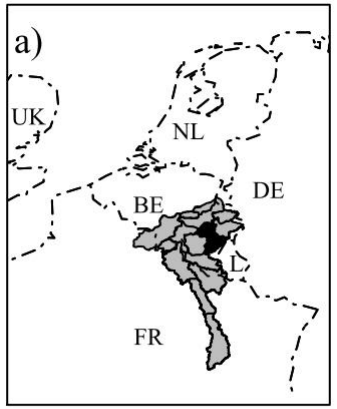
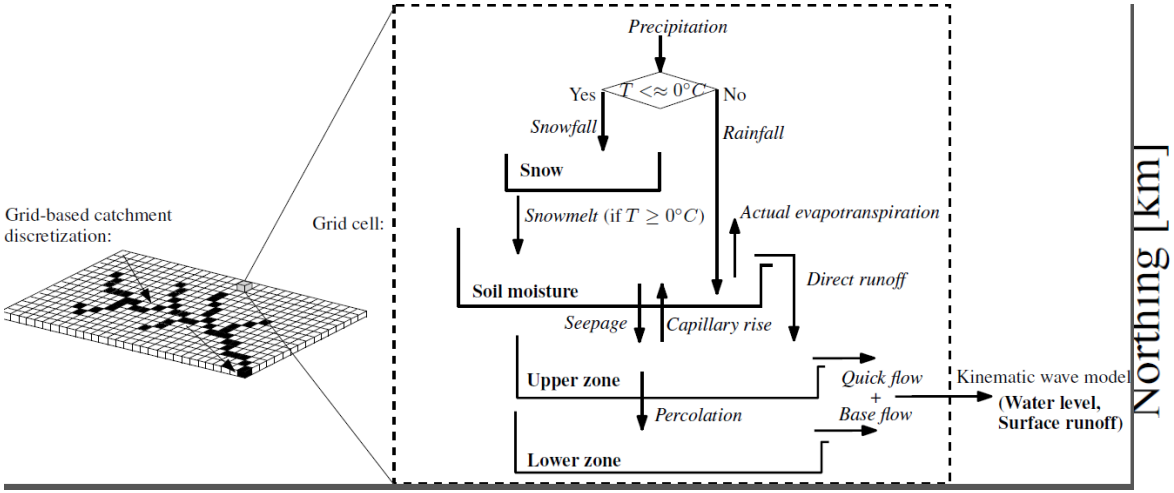
State updating using distributed hydrologic model

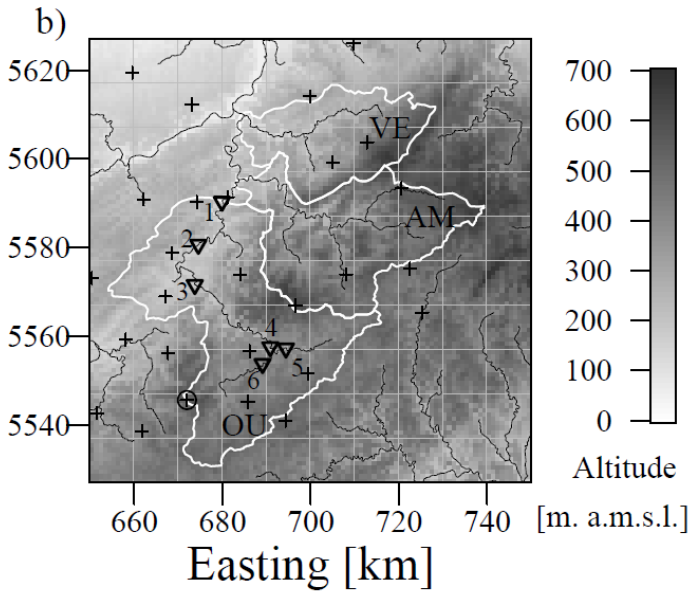
Rakovec et al. (2012a) presented a spatially distributed hourly ensemble rainfall generator which was used in Rakovec et al. (2012b) to study effect of update frequency, number and location of streamflow gauges



HBV-96



1 km^2



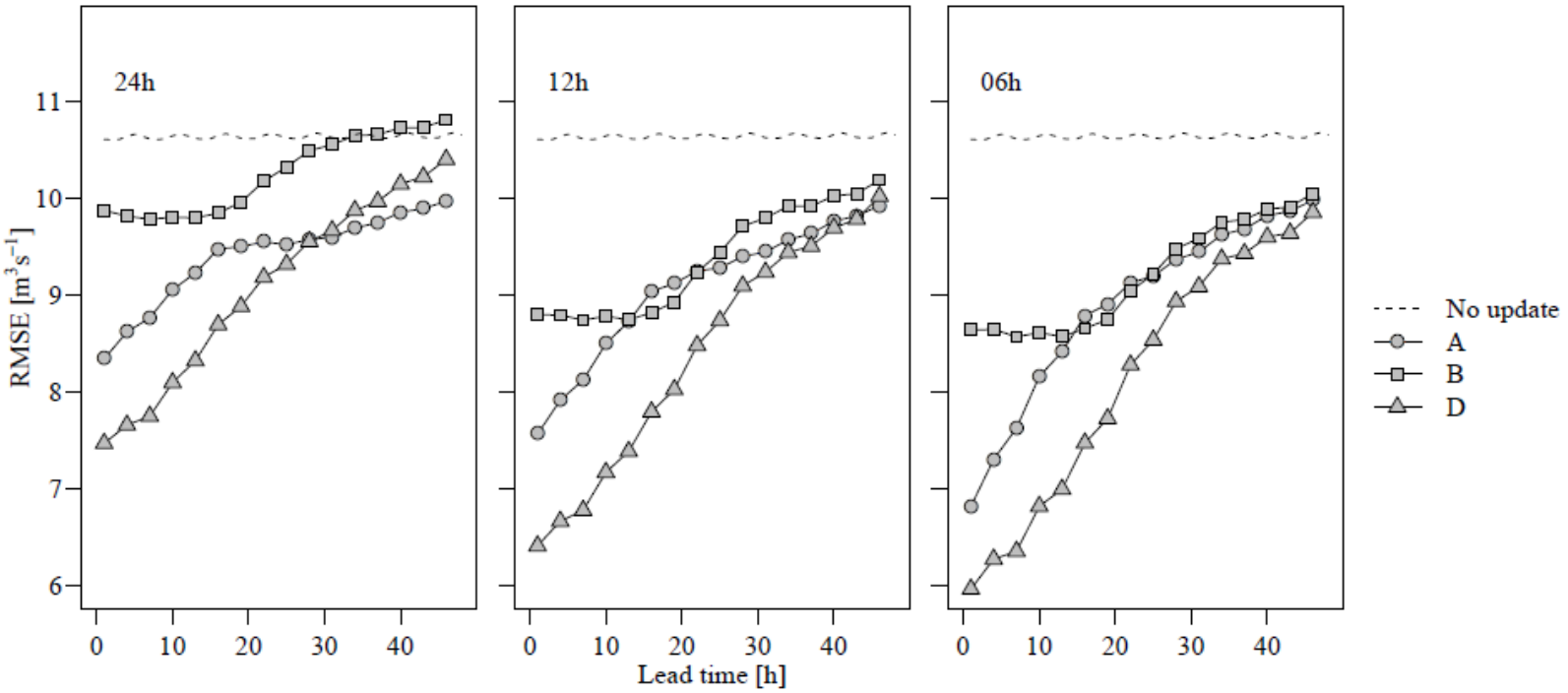


Fig. 8. Real world experiment, simulation period from 15 August 2002 to 15 January 2003. Root-mean-square error at Tabreux for different discharge observation vectors. Forecast issued every 6 h. EnKF assimilation every 24 h (left), 12 h (centre), 6 h (right).

Conclusions:

- 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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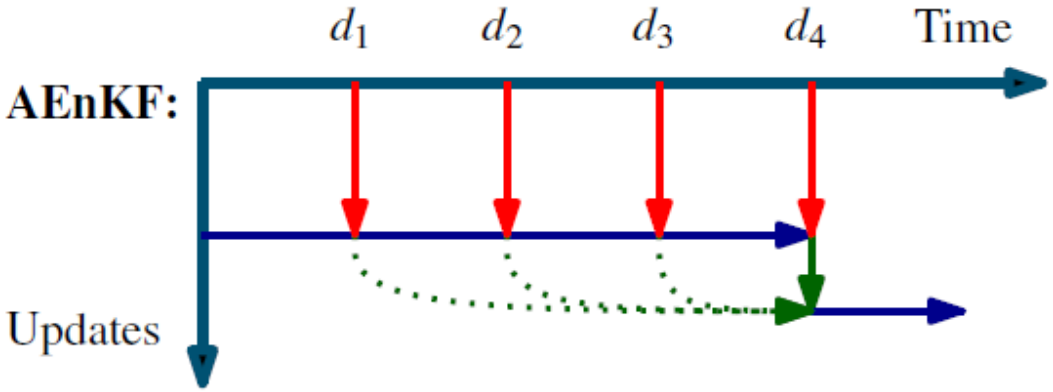
Operational aspects of asynchronous filtering

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. 2014 (submitted to WRR)

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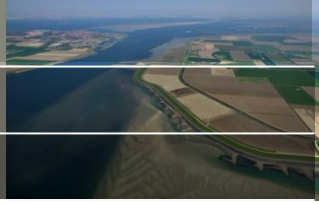

EnKF updates model states at time k as:

$$\mathbf{X}_k^+ = \mathbf{X}_k^- + \mathbf{K}_k(\mathbf{y}_k - \mathbf{H}_k\mathbf{X}_k^-),$$

where $\mathbf{X}_k^+$ is the new updated (posterior) model state matrix, $\mathbf{X}_k^-$ is the forecasted (prior) model state matrix. $\mathbf{K}_k$ is the Kalman gain (a weighting factor of the errors in model $\mathbf{H}_k\mathbf{X}_k^-$ and observations $\mathbf{y}_k$)

Asynchronous EnKF is a simple modification of the EnKF, in which $\mathbf{X}_k$ is augmented with the past forecasted observations from W previous time steps $\mathbf{H}_k\mathbf{X}_k$:

$$\tilde{\mathbf{X}}_k = \begin{pmatrix} \mathbf{X}_k \\ \mathbf{H}_{k-1}\mathbf{X}_{k-1} \\ \mathbf{H}_{k-2}\mathbf{X}_{k-2} \\ \vdots \\ \mathbf{H}_{k-W}\mathbf{X}_{k-W} \end{pmatrix}$$

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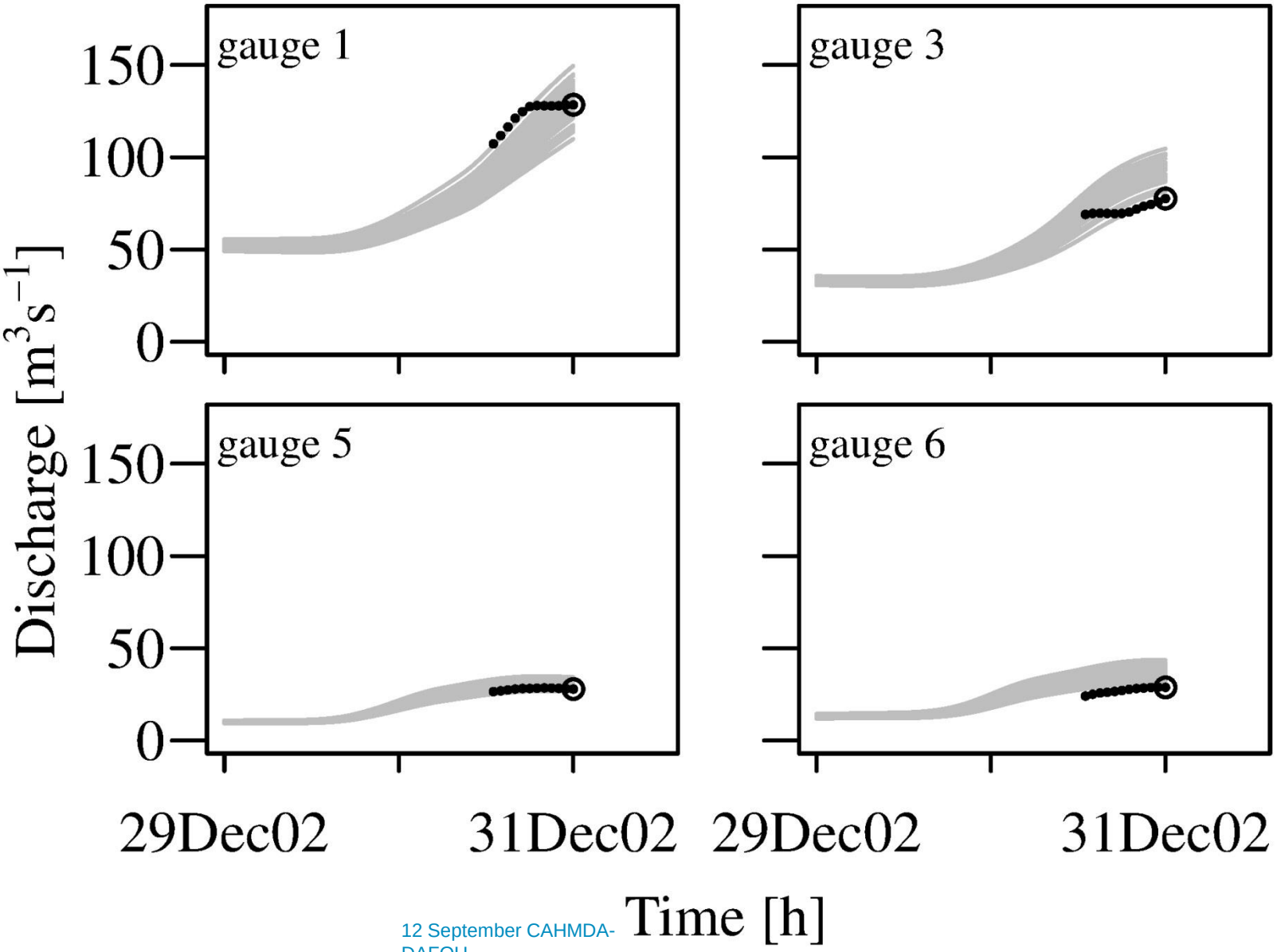
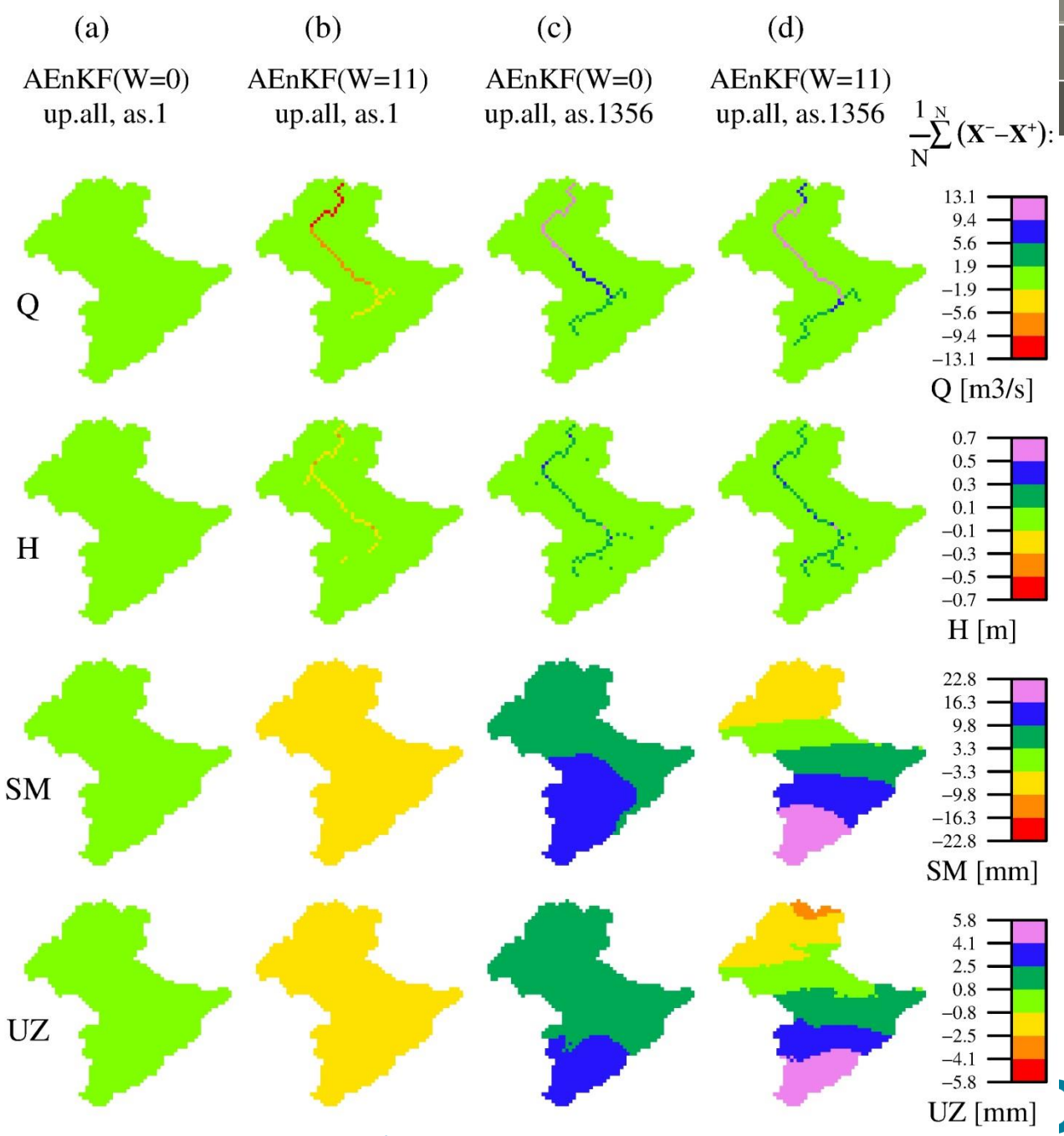
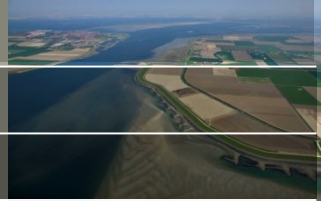

gauge 1
gauge 3
gauge 5
gauge 6
150
100
50
0
Discharge [m^{3}s^{-1}]
29Dec02
31Dec02
29Dec02
31Dec02
Time [h]


(a)
AEnKF(W=0)
up.all, as.1
(b)
AEnKF(W=11)
up.all, as.1
(c)
AEnKF(W=0)
up.all, as.1356
(d)
AEnKF(W=11)
up.all, as.1356
$\frac{1}{N}\sum^{N}(X^{-}-X^{+})$:
Q
13.1
9.4
5.6
1.9
−1.9
−5.6
−9.4
−13.1
Q [m3/s]
H
0.7
0.5
0.3
0.1
−0.1
−0.3
−0.5
−0.7
H [m]
SM
22.8
16.3
9.8
3.3
−3.3
−9.8
−16.3
−22.8
SM [mm]
UZ
5.8
4.1
2.5
0.8
−0.8
−2.5
−4.1
−5.8
UZ [mm]

Experimental setup



- 8 largest flood peaks observed since 1998
- Model noise: perturbation of soil moisture reservoir with spatio-temporally correlated error model (36 members)
- Sensitivity of the AEnKF to the assimilated time window: $W = 0h$, $W = 5h$, $W = 11h$
- Four partitioned state updating schemes for model states being updated (thus included in the model analysis).

name	Q	H	SM	UZ	LZ
no update					
all	√	√	√	√	√
noSM	√	√		√	√
HQ	√	√			

Model states: discharge (Q), water level (H), soil moisture (SM), upper zone (UZ), and lower zone (LZ). Snow and interception storages not shown.

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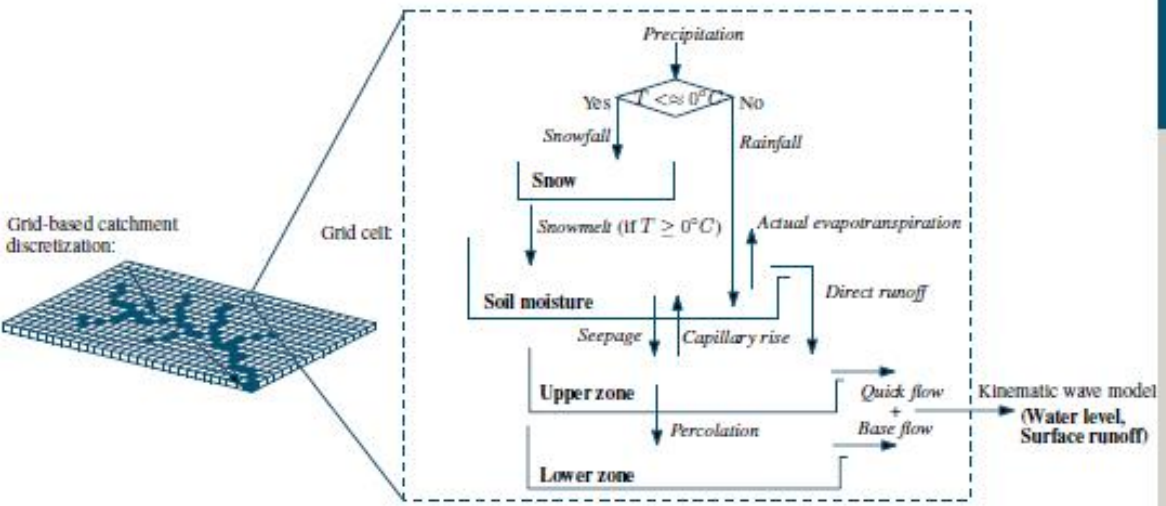
Experimental setup

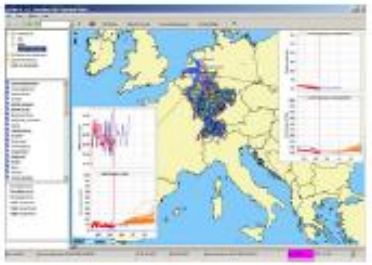


Conceptualization into a **grid**

- 1km^2 resolution
- 8 model states
- Lumped routing substituted by KW model

OpenStreams

OpenDA



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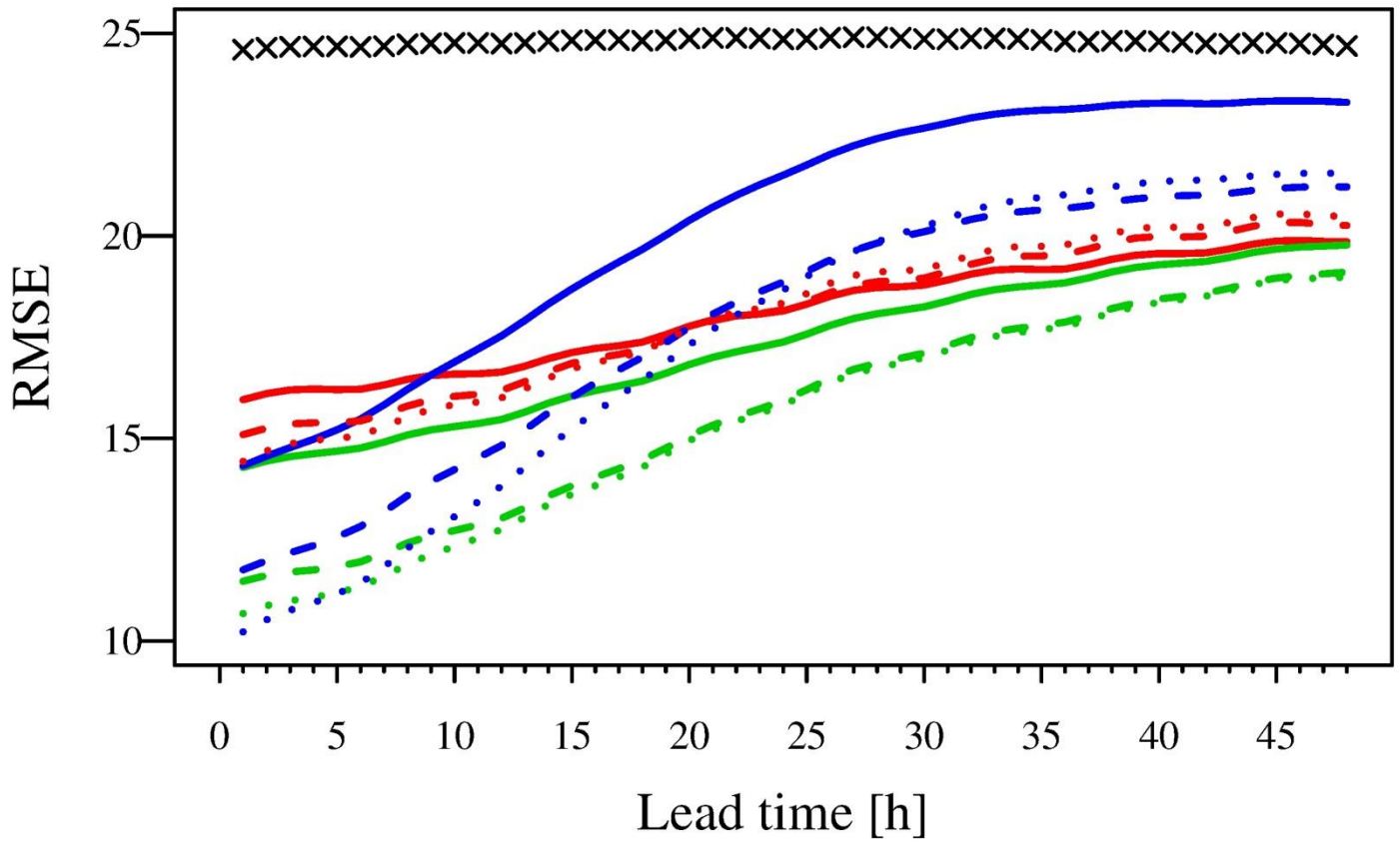
Results



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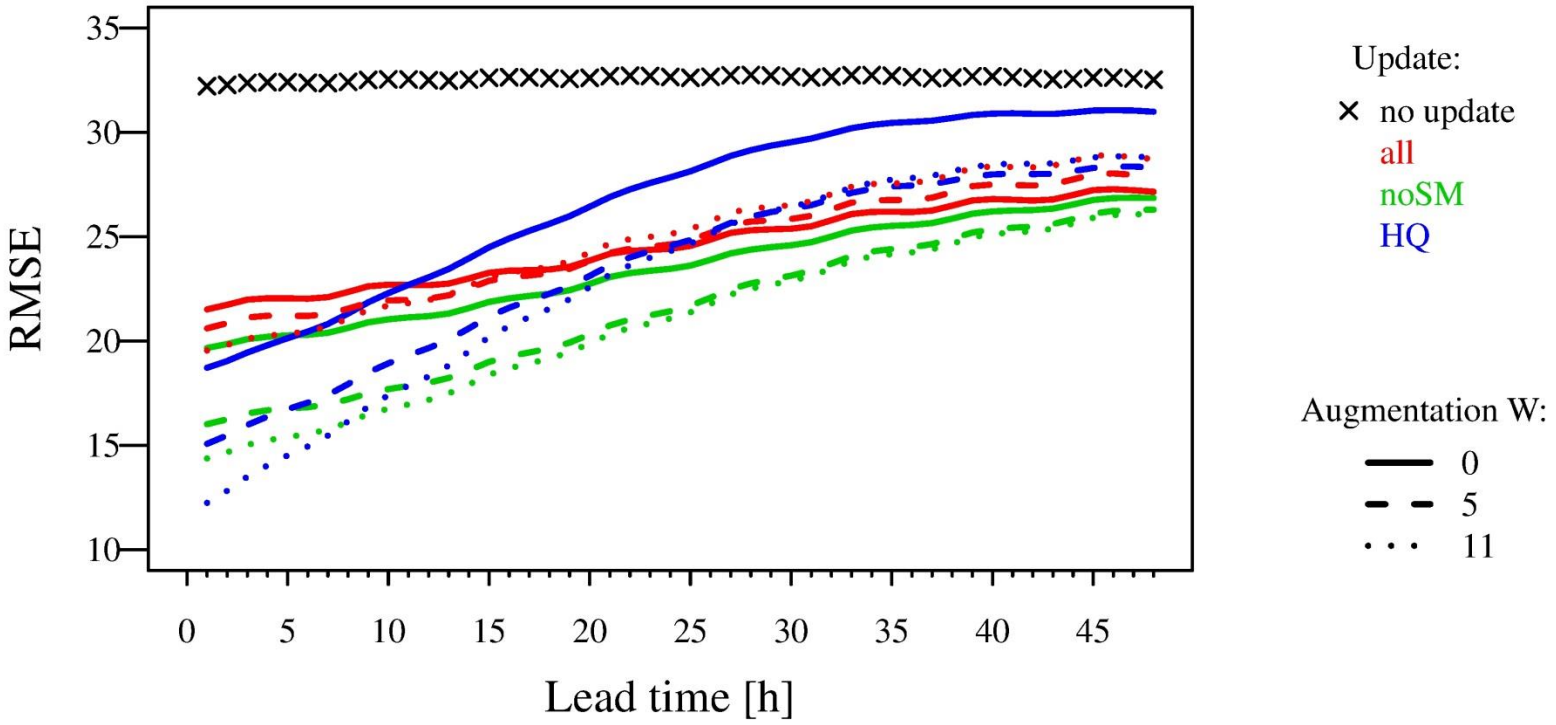
Validation



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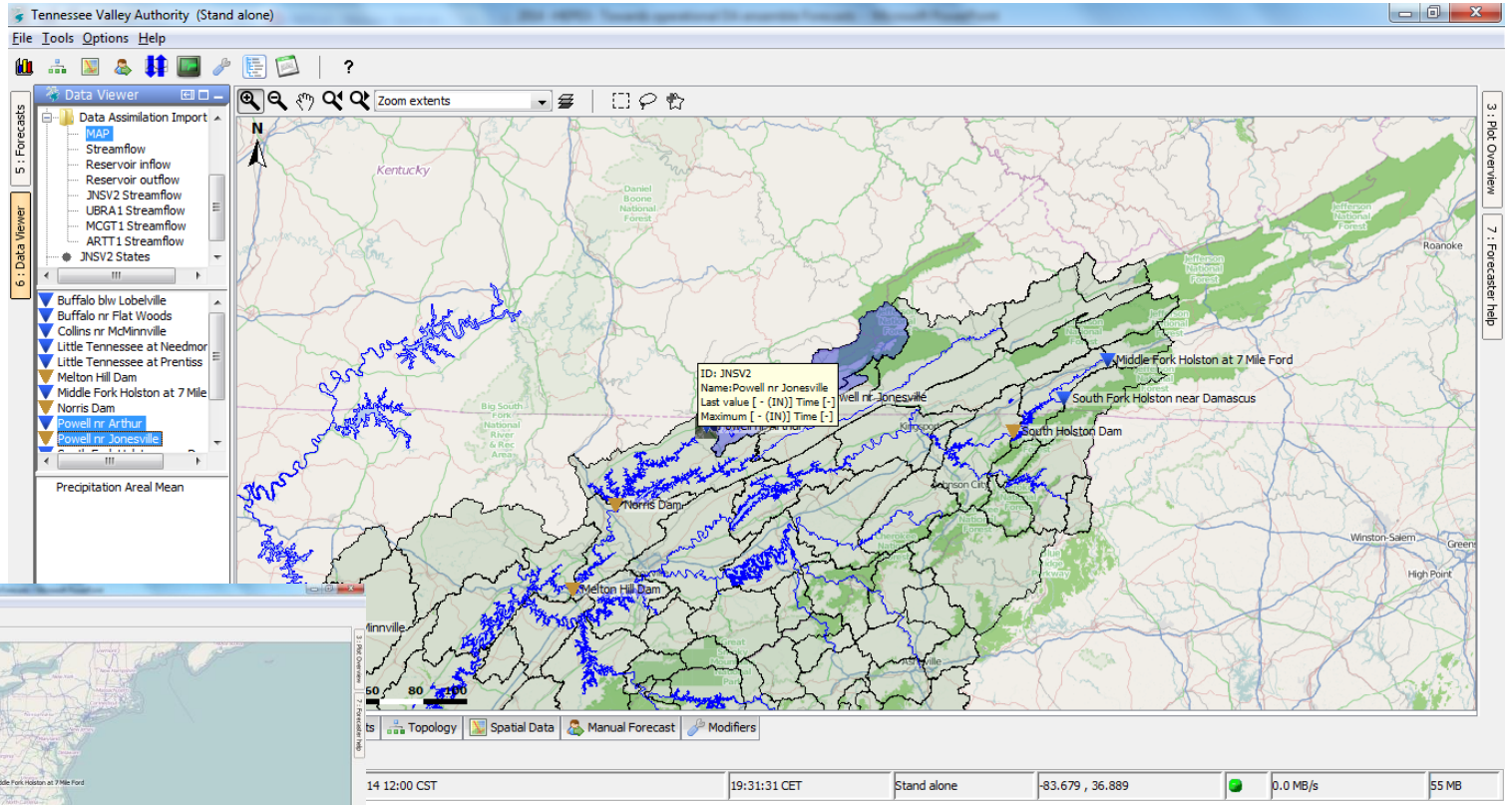
2nd example is work in progress…

With RTI, NCAR & Deltares USA for Tennessee Valley Authority

Main goal: Guide the manual modification process and realize considerable time gains



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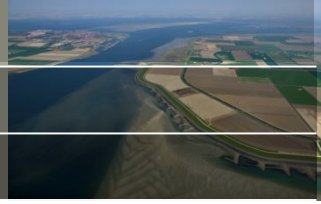

- Delft-FEWS is wrapped (via piwebservice) in OpenDA to enable parallel execution of FEWS workflows (and the chained models within these workflows, including SACSMA, UNITHG and LAGK) in a DA framework;

- Multiple DA algorithms configured for testing
  - EnKF, AEnKF, PF, (DEnKF, EnSR,…), etc

- Verification results for a variety of basins (4) will be presented at AGU 2014;

- Current idea is that the Ensemble DA analysis runs provide a single (mean) estimate of the state at T0 which will be used to determine the MOD in an automated manner and present this to the forecaster as a suggestion for a deterministic forecast;

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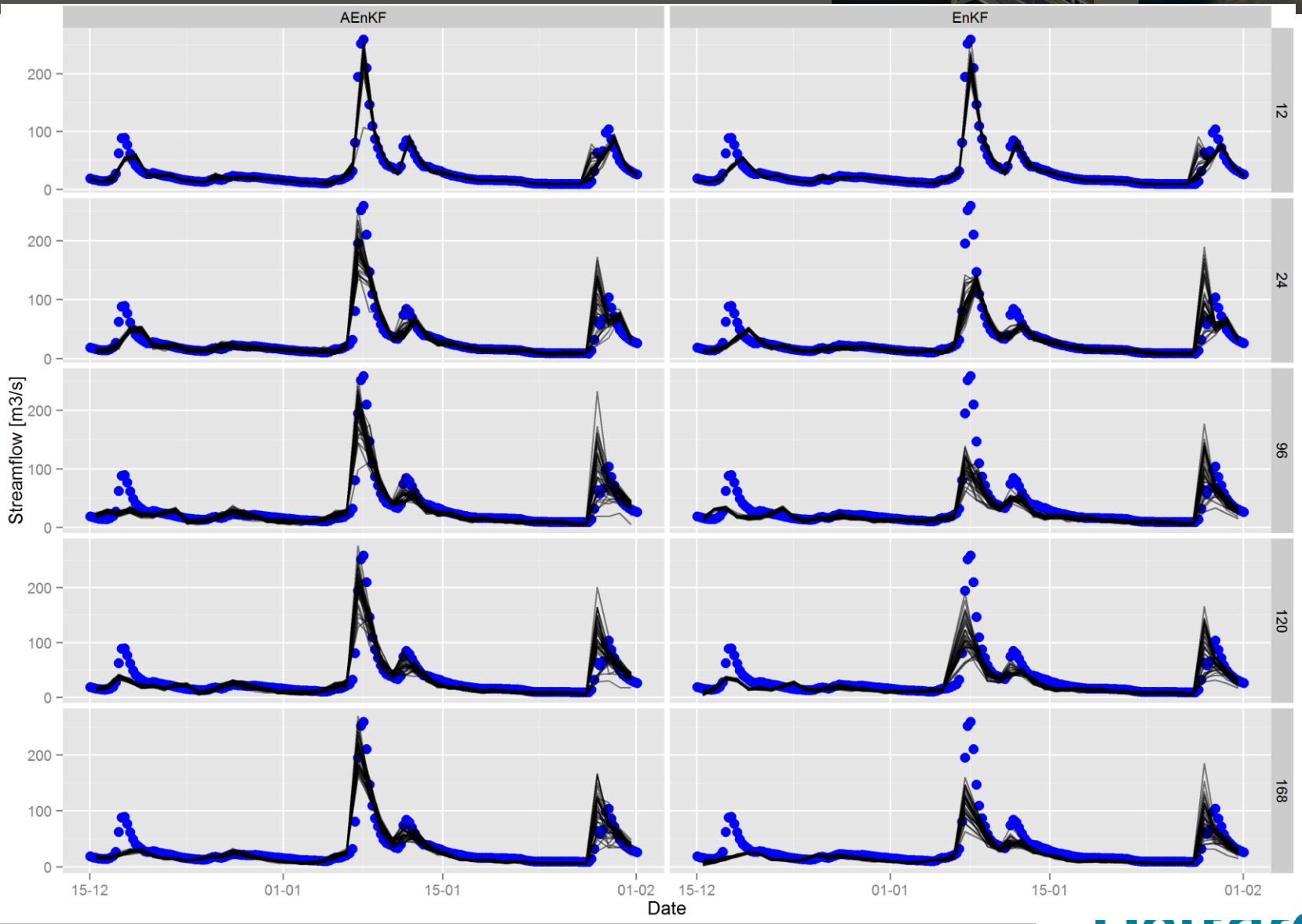
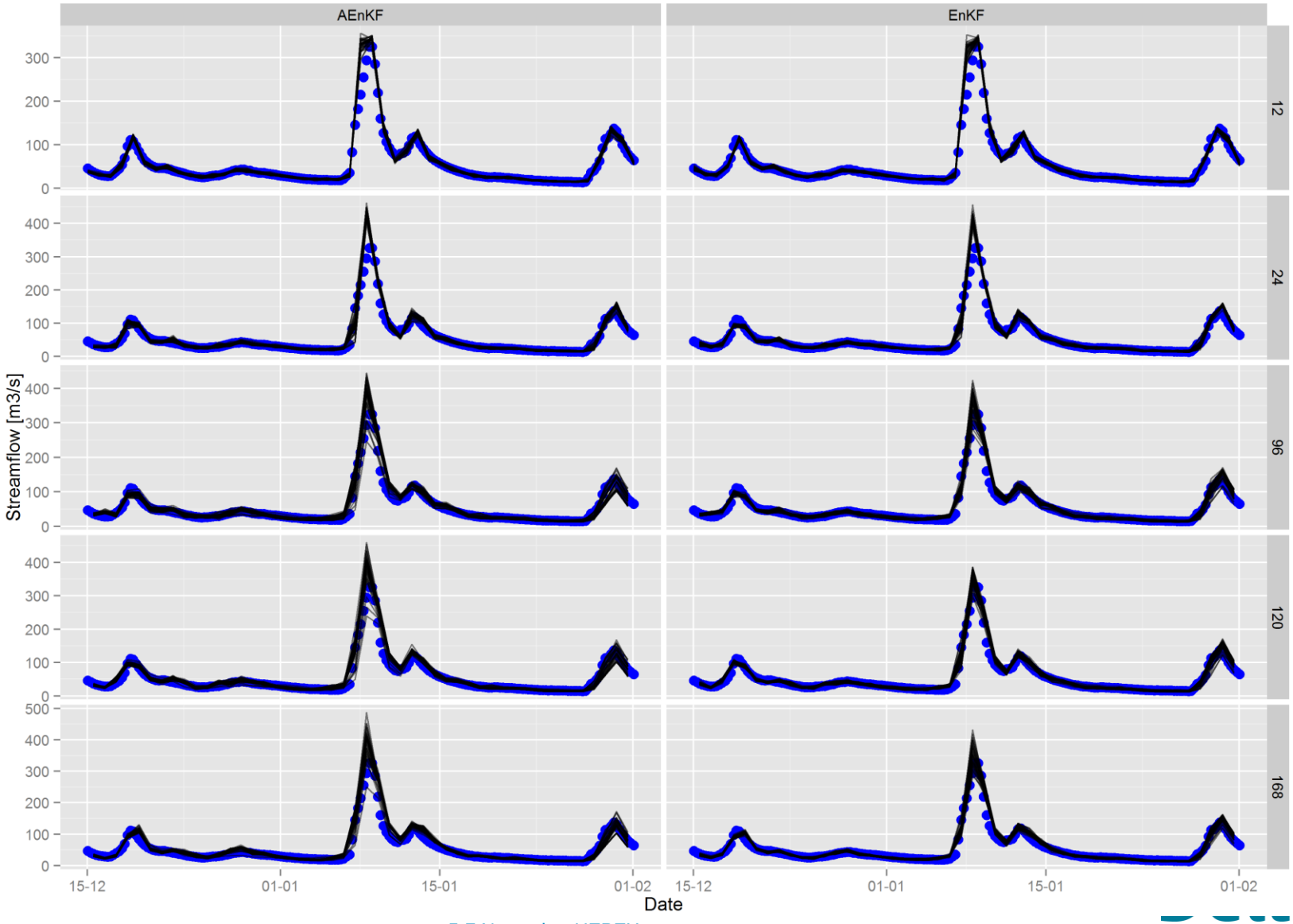
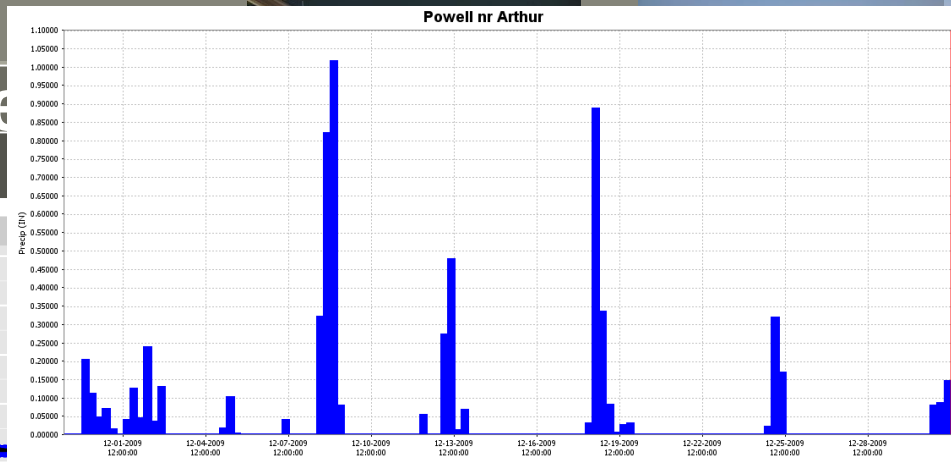
JNSV2 (Upstream) Dec 2008-Jan 2009

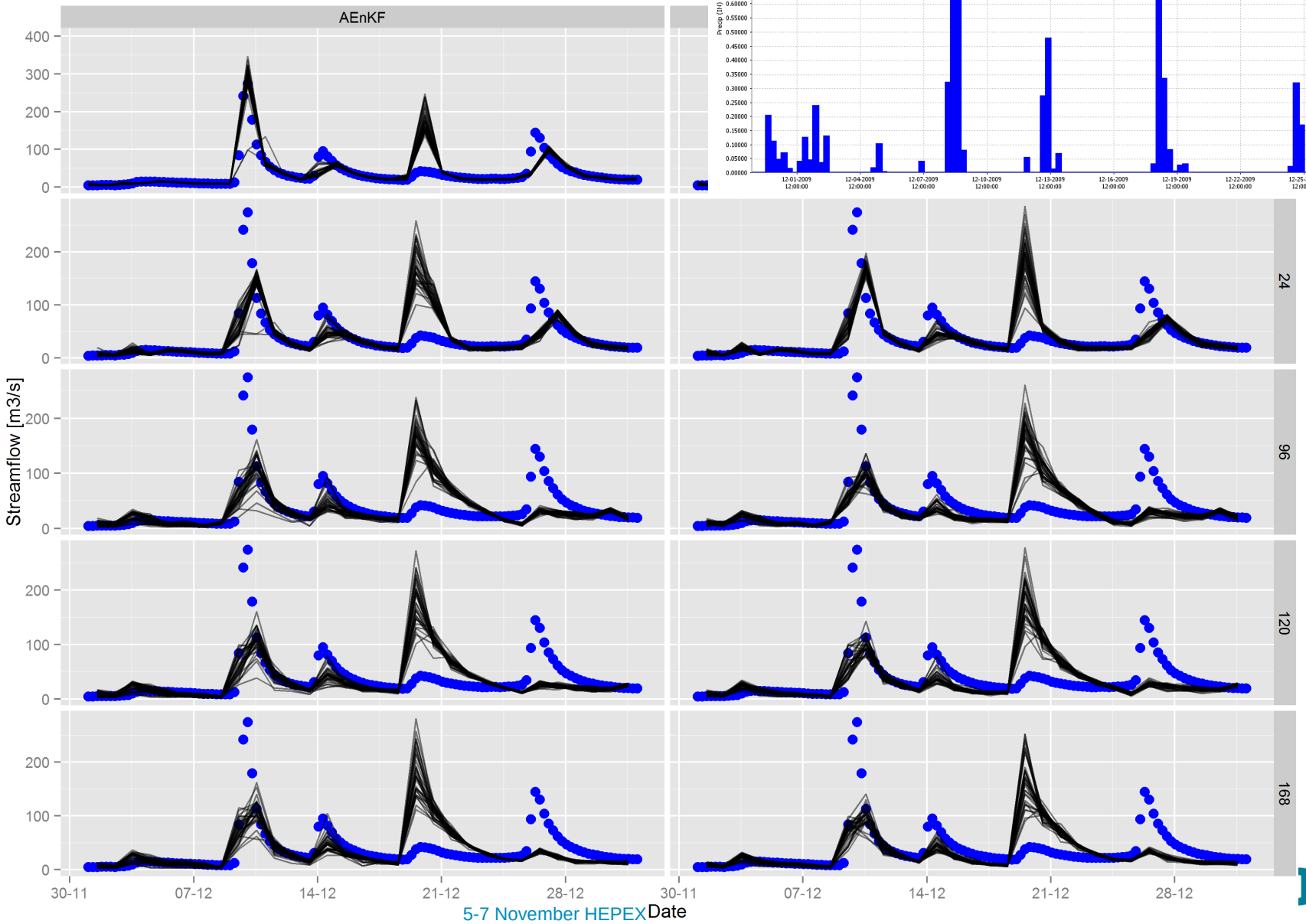


ARTT1 (Downstream) Dec 2008-Jan 2009

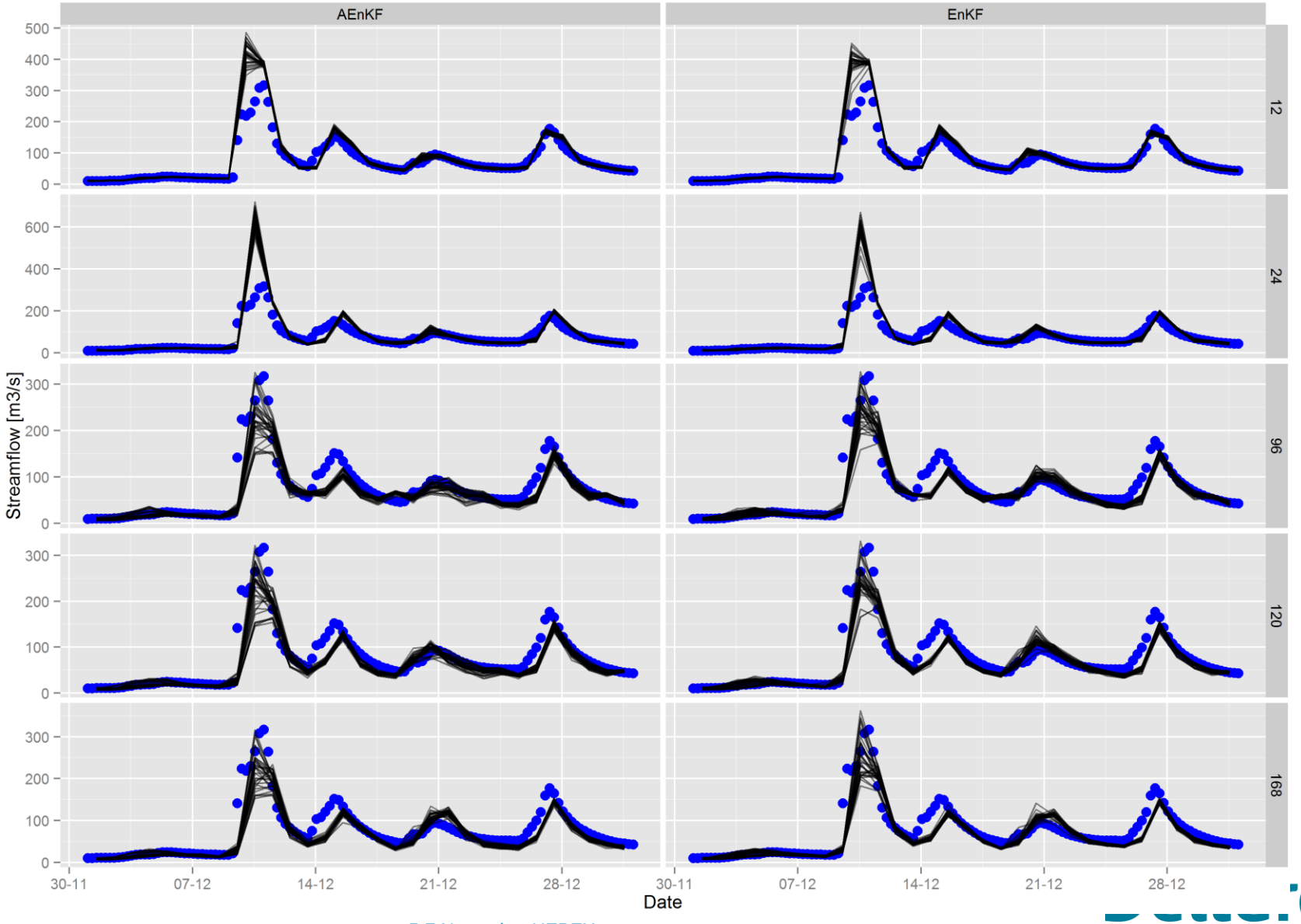


JNSV2 (Upstream) Dece

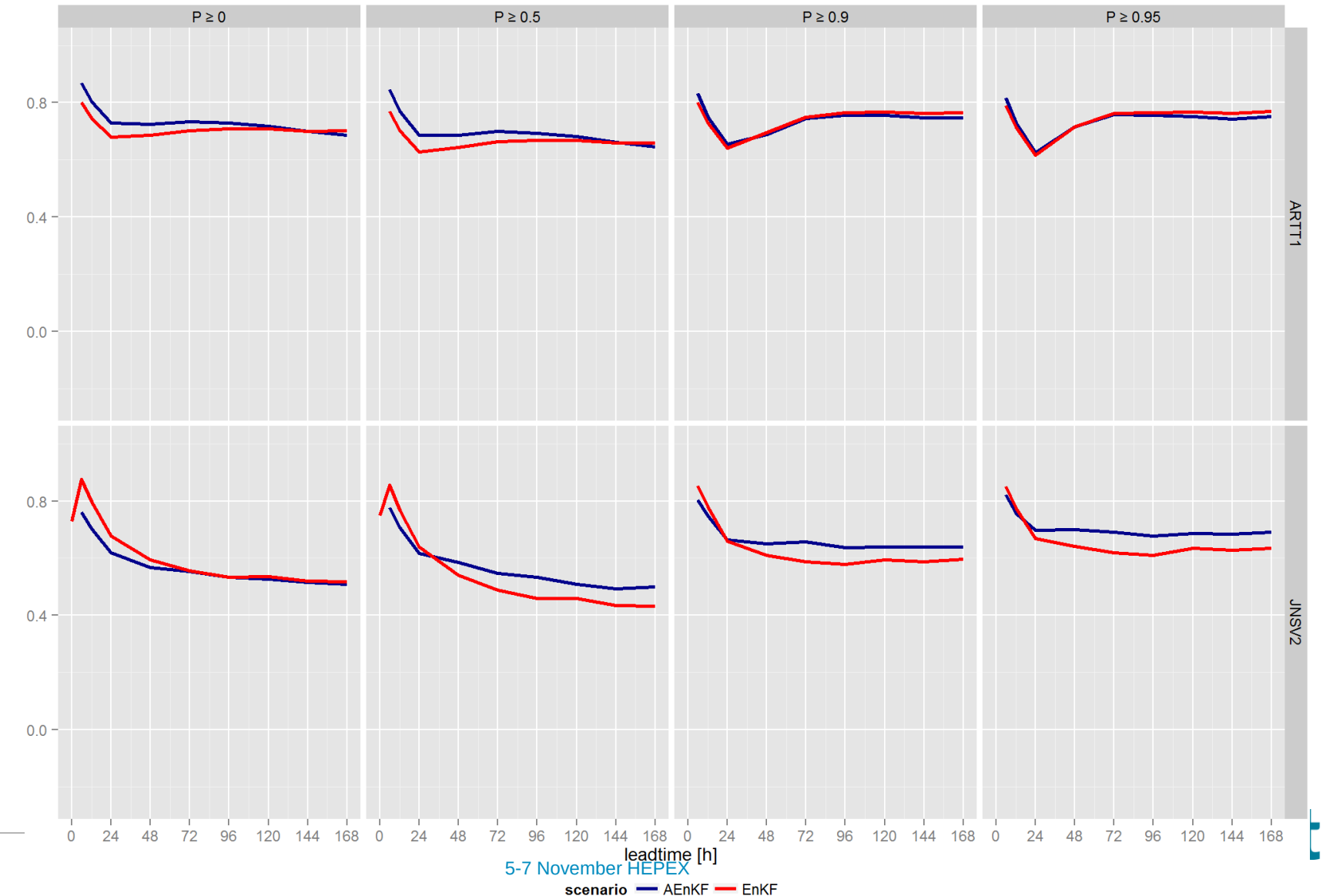




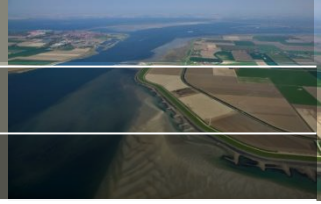
ARTT1 (Downstream) December 2009



CRPSS (whole period 2008-2011)



Concluding remarks



- A lot of research has been conducted the last couple of years on the topic of Hydrologic Ensemble DA;
- In operational hydrologic DA, there is not yet a preferred DA method, AEnKF seems like a promising alternative to EnKF (and maybe variational methods shown before as well, MLEF presented at CAHMDA-DAFOH III also showed promise);
- Operational ensemble based (guided) DA is becoming feasible and the obstacles for usage are mainly institutional (e.g. resources, forecasts process, other priorities, etc);
- Community-based generic modeling/DA tools are needed and a useful tool also to cross the bridge between research and operations;