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Enabling Delta Life

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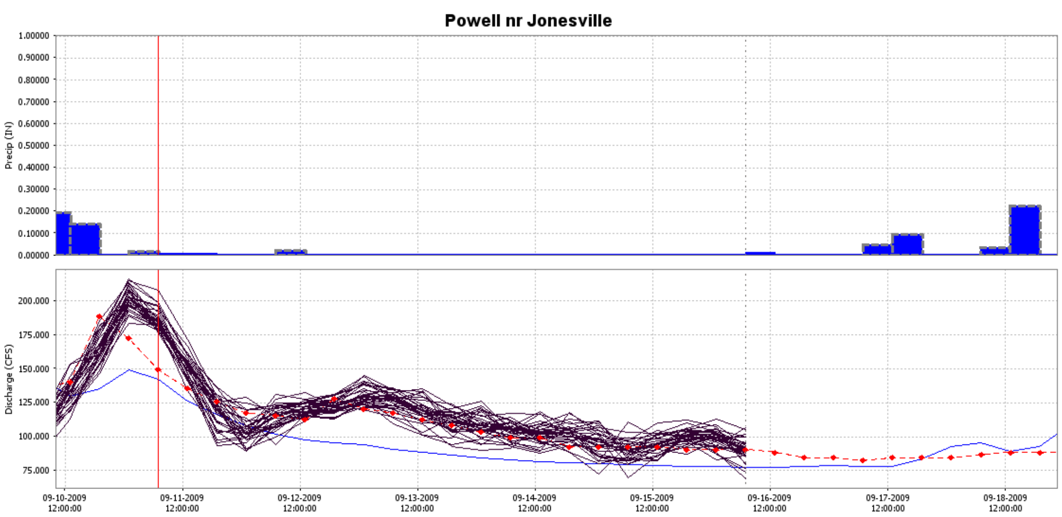
Towards operationalizing ensemble DA in hydrologic forecasting

Albrecht Weerts

12 September CAHMDA-DAFOH



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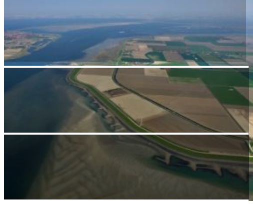
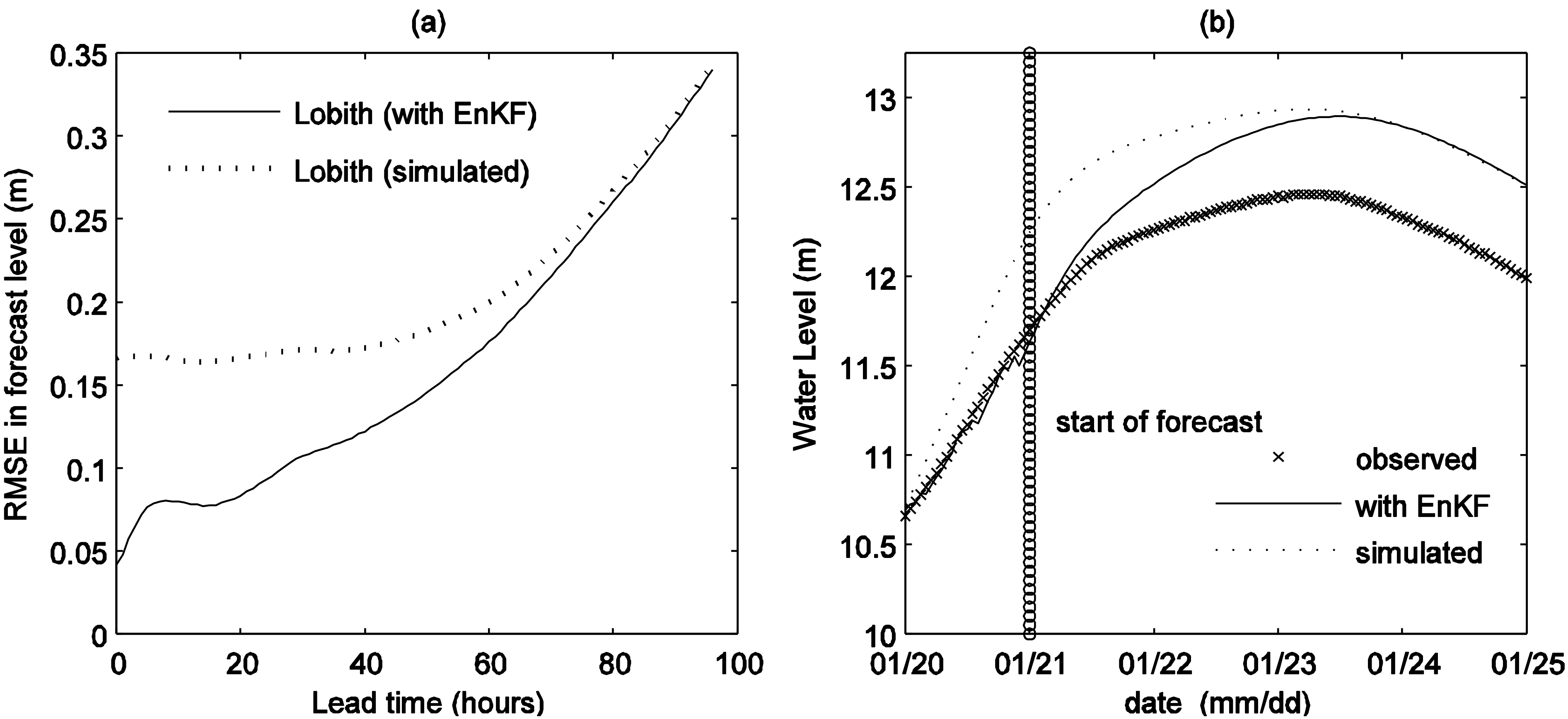
Deltares, P.O. Box 177, 2600 MH, Delft, The Netherlands

See also Werner et al., 2014



Results EnKF at Lobith over 2 year hindcast (2006/2007)



Januari 2007

Different forecasting paradigms

North America	**Europe**
Primarily Manual process	Primarily Automated process
– Forcings QC in-house	• Forcings QC out-of-house
– Interactive Forecasting	• Automated Forecasting
– Involved	• Observant
– Low-frequency (daily)	• High frequency (hourly)
– 6 hr timesteps	• Hourly time steps
– Ensembles climatology based	• Ensembles NWP based

From Gijsbers et al. 2011

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Some conclusions from the workshop in 2010

- Role forecaster!
  - different for each organisation / institutional setup

- Manual vs Automated DA approach
  - Europe mainly automated (deterministic)
  - USA often manual => Runtime MODIFICATIONS
    - > Using observed streamflow to infer appropriate adjustments to:
      - – Model states
      - – Timing and magnitude of forcings

- Changes in budget/priorities or other outside factors

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pro’s / con’s automated DA

Essential in “fast response” situations where there is no time for manual analysis;

Consistent DA is more reproducible than subjective forecaster specified adjustments.

Updates to improve performance in one time domain (e.g. short) may degrade performance in another (e.g. long);

Improved simulation does not guarantee improved forecast performance;

Forecasters don’t (won’t) trust what they can’t see or understand;

May reduce the need for the forecaster to understand what the models are doing (Robotic Operations).

some workshop conclusions..

Operational forecasters perform *manual* data assimilation by leveraging their expertise

Automatic DA is critical for very short lead times where manual analysis is not feasible

DA techniques should be engineered to assist the forecaster in *understanding and applying* the most appropriate adjustments suggested by the data (guidance)

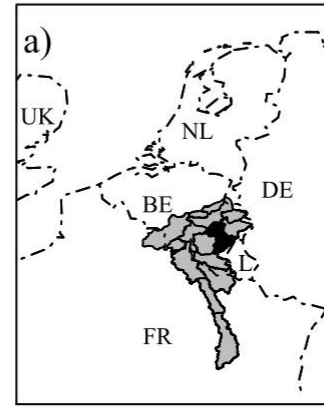
Development, implementation and institutionalization of forecaster-supervised automatic DA in operational hydrology will require:

- Collective efforts from both the research and the operational communities
- Cross-cutting community planning and action to capitalize on recent advances and to seize the window of opportunity

So where are we?

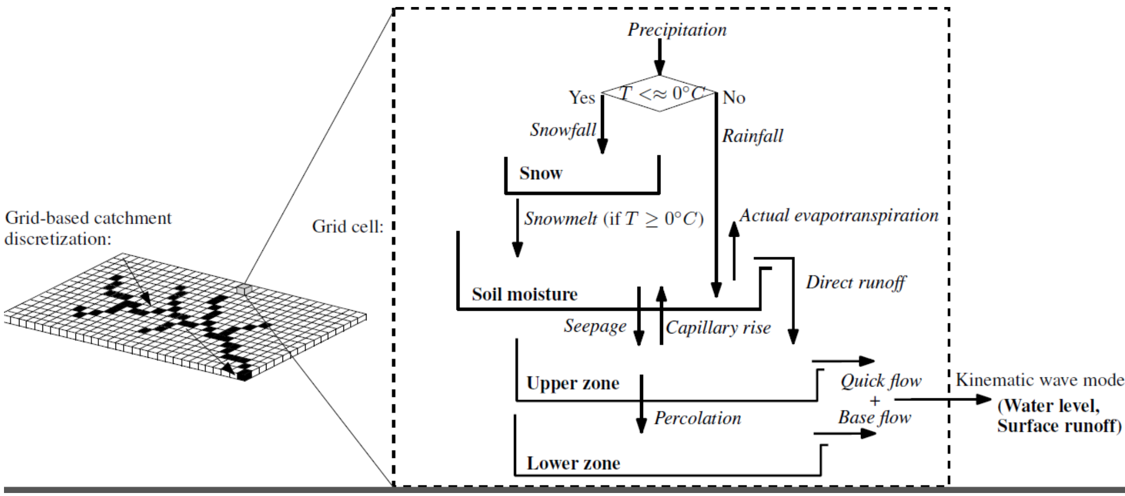
- Joint paper in HESS 2012 Liu et al. 2012 (cited 41 times scholar.google.com) as result of workshop in Delft
- Main challenges for operational hydrologic DA:
  - theoretic or mathematical challenges;
  - characterization of uncertainties;
  - Integrating newly emerging observations such as remote sensing data;
  - real-time control of water resources systems and hydraulic structures;
  - community-based approach to hydrologic DA
    - verification
    - developing community-based generic modeling/DA tools

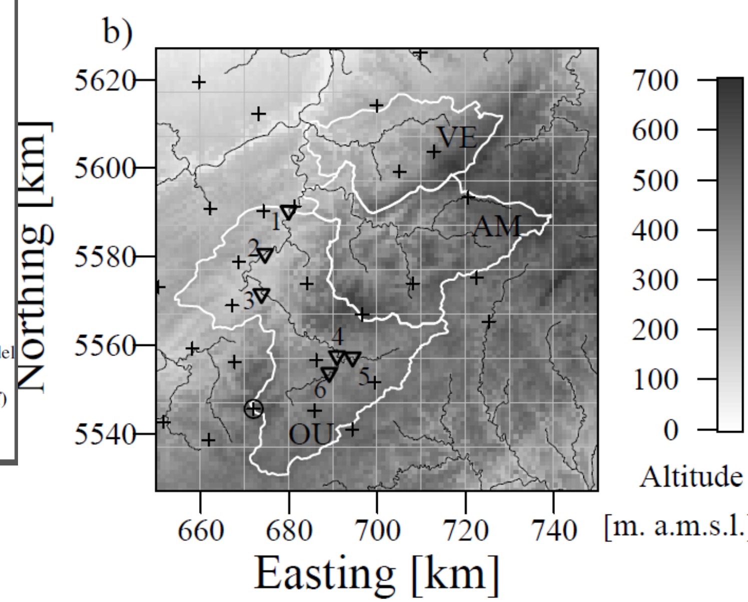
Characterization of uncertainties - I



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

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Characterization of uncertainties - I

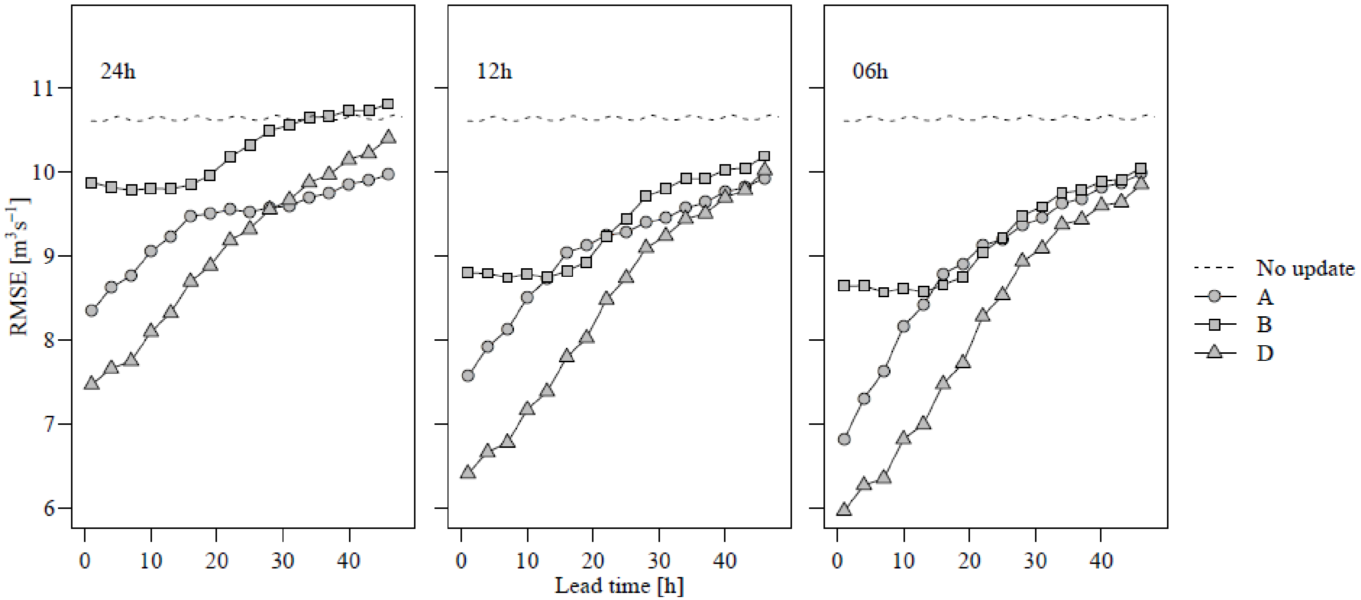

Fig. 8. Real world experiment, simulation period from 15 August 2002 to 15 January 2003. Root-mean-square error at Tabreux for different discharge observation vectors. Forecast issued every 6 h. EnKF assimilation every 24 h (left), 12 h (centre), 6 h (right).

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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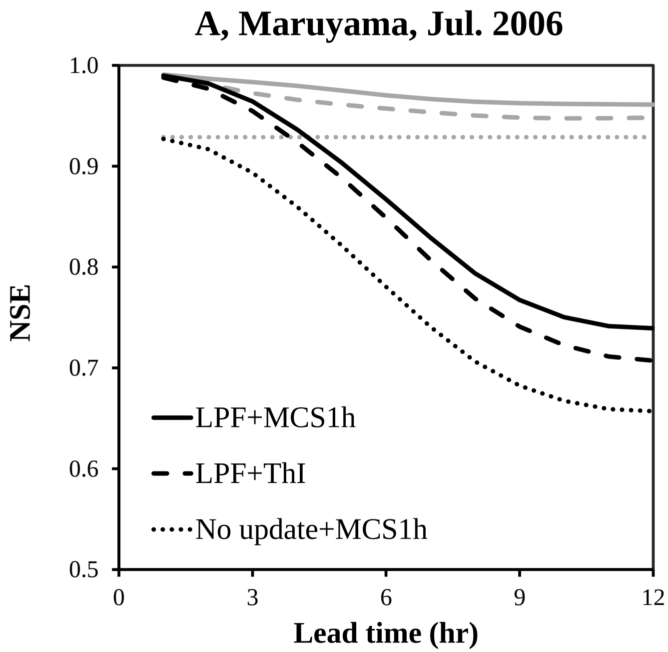
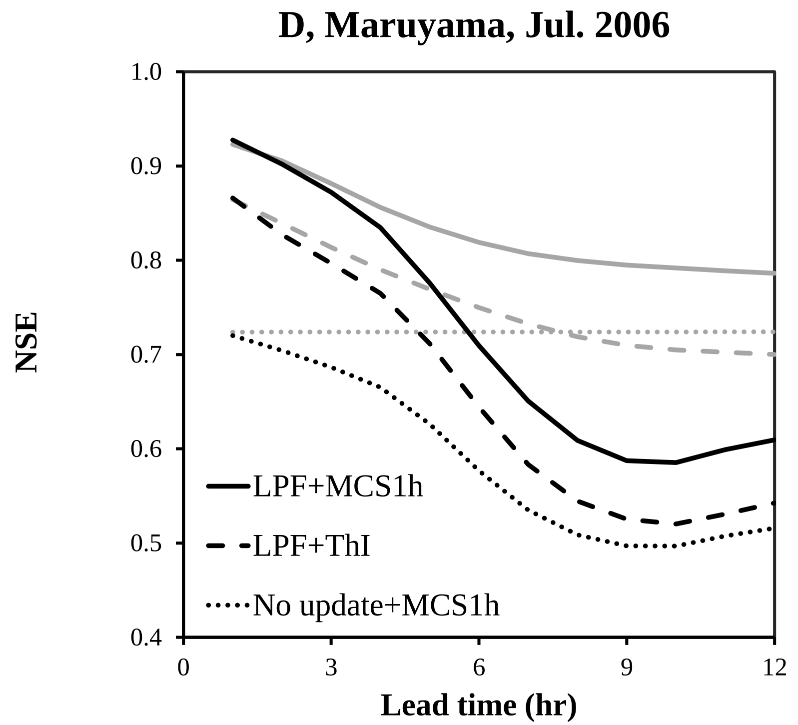
Characterization of uncertainties - II

In Noh et al (2014) the rainfall generator of Rakovec et al. (2014) was used in combination with the lagged particle filter (Noh et al, 2011) to study the effect of noise on the DA results on 3 Catchments in Japan.

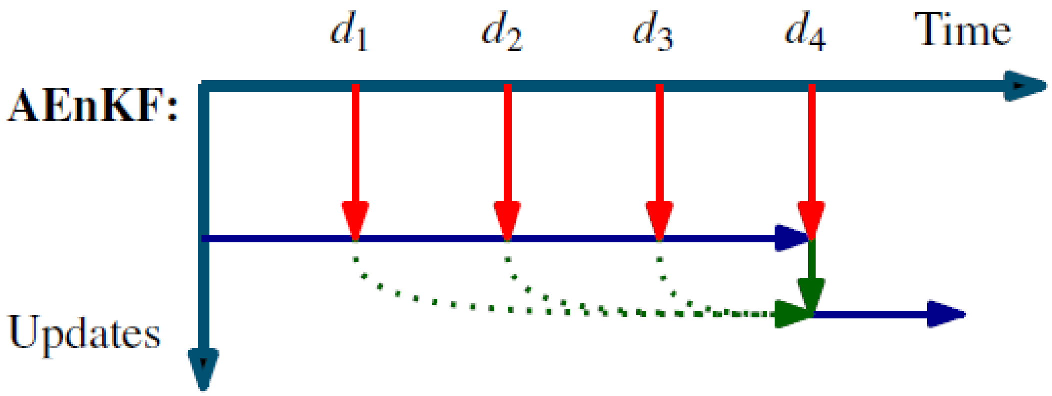




Conclusions: results show that better specification of input noise requires smaller noise on state variables to get similar performance

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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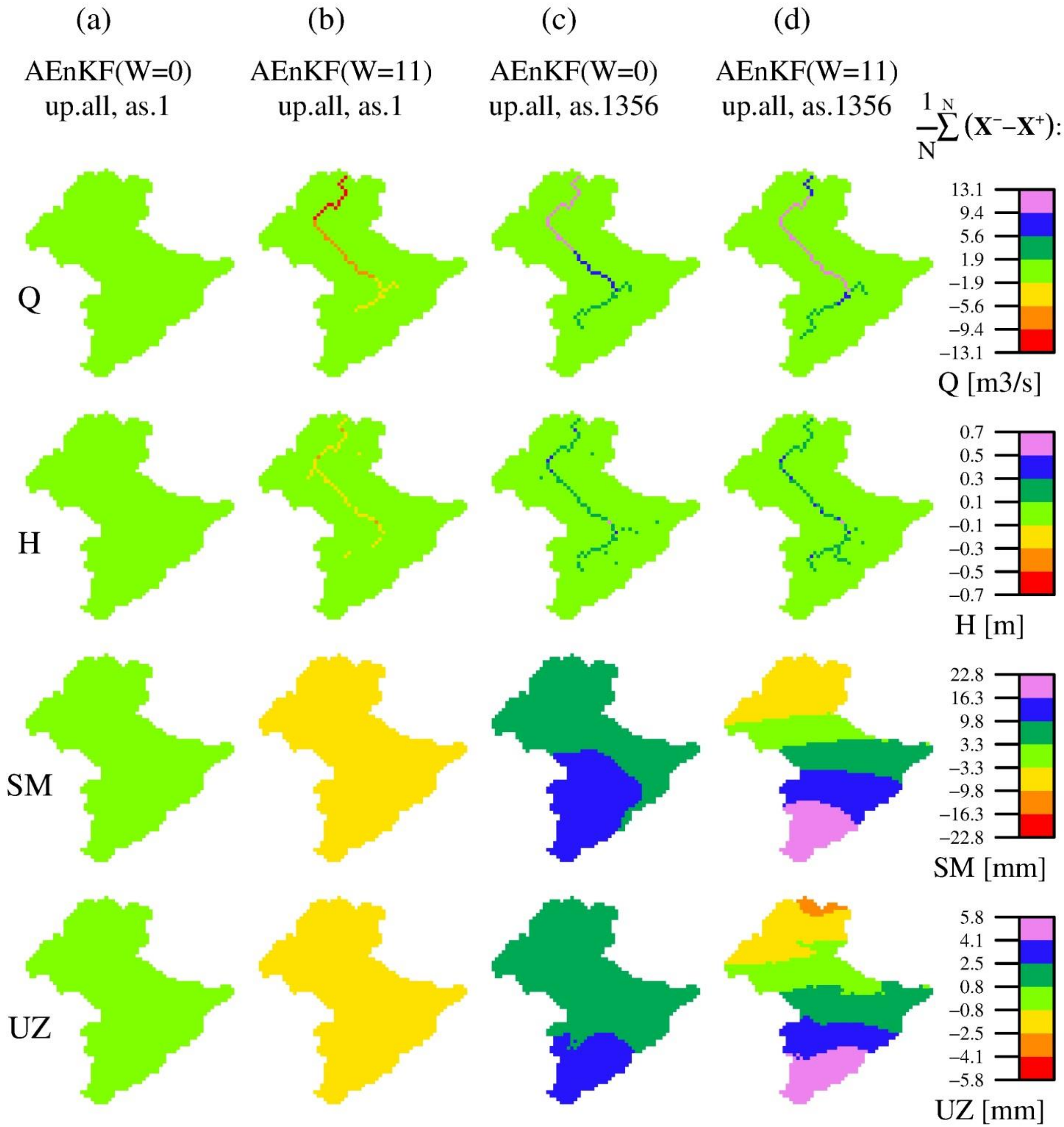
EnKF updates model states at time k as:

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

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 $\boldsymbol{y}_k$)

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 $\mathbf{H}_k\mathbf{X}_k$:

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



(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
H
SM
UZ
13.1
9.4
5.6
1.9
−1.9
−5.6
−9.4
−13.1
Q [m3/s]
0.7
0.5
0.3
0.1
−0.1
−0.3
−0.5
−0.7
H [m]
22.8
16.3
9.8
3.3
−3.3
−9.8
−16.3
−22.8
SM [mm]
5.8
4.1
2.5
0.8
−0.8
−2.5
−4.1
−5.8
UZ [mm]


- 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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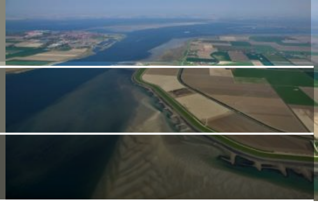
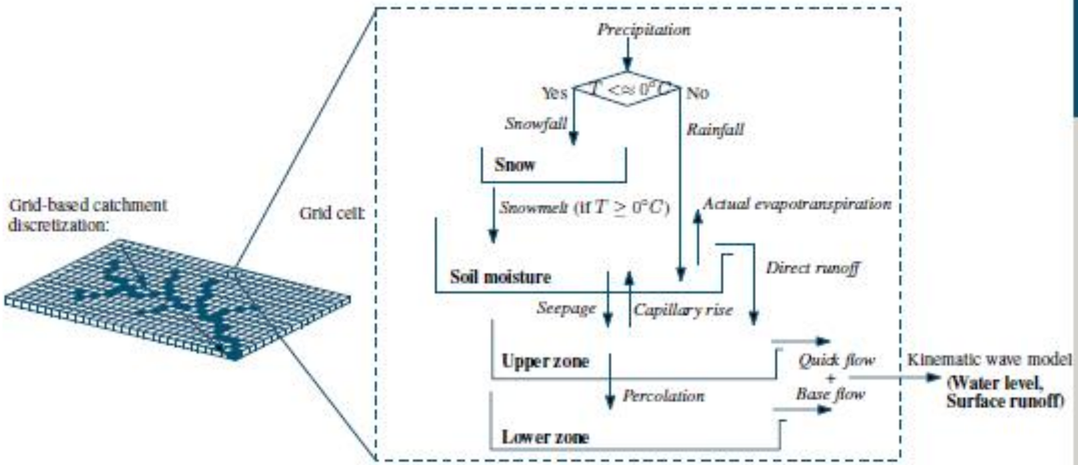


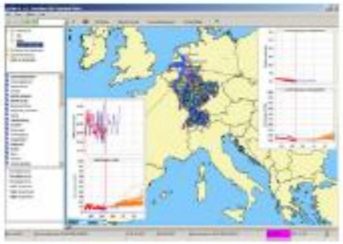
Conceptualization into a **grid**

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



OpenStreams

OpenDA



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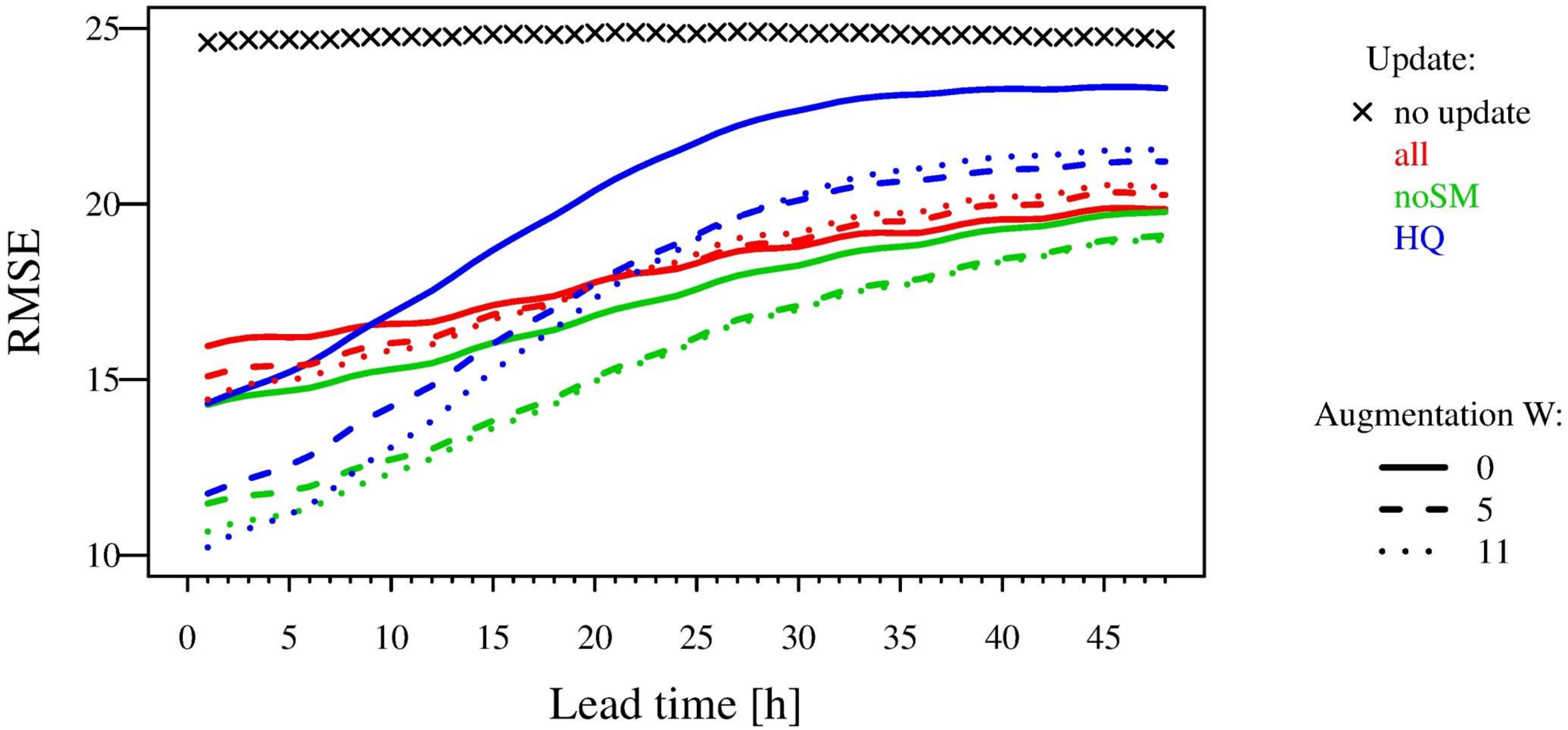
Results



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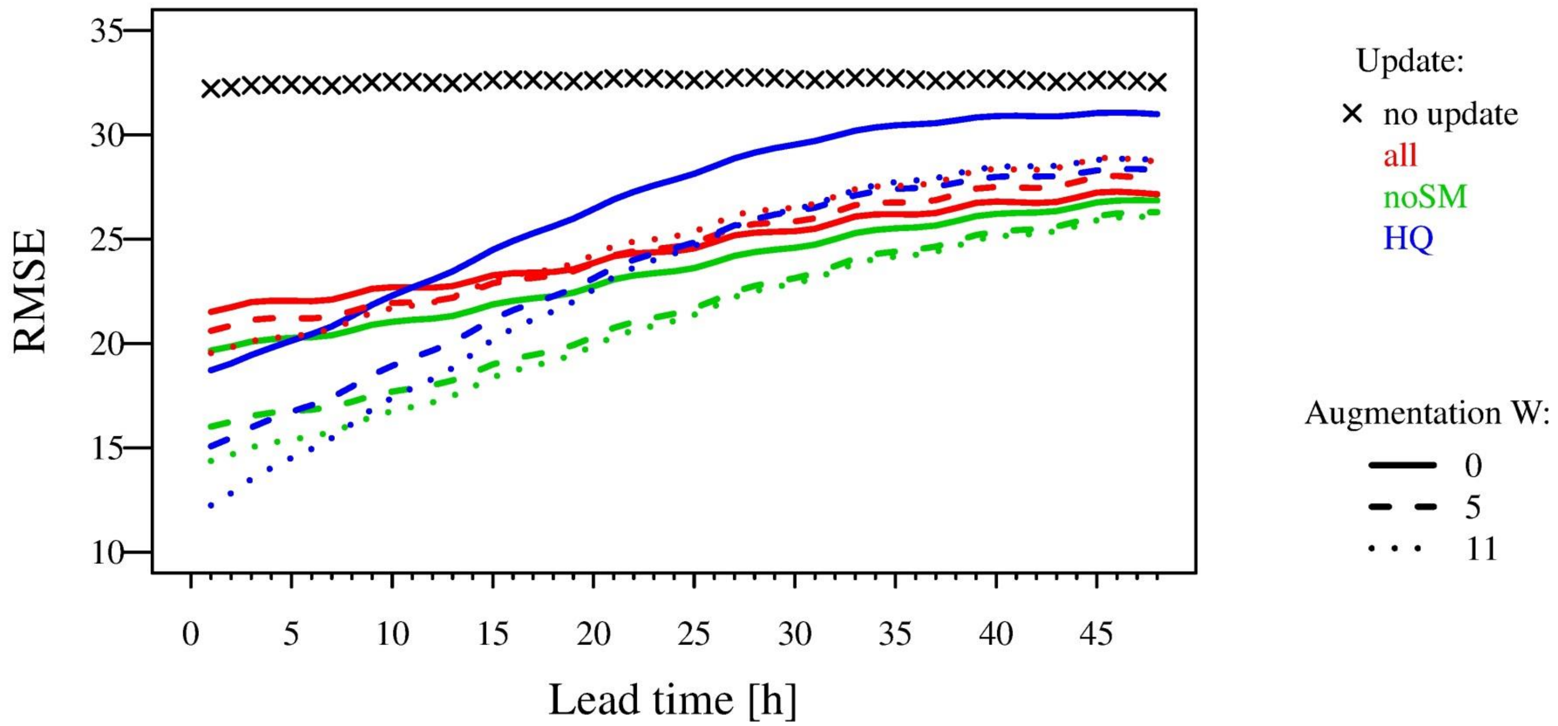
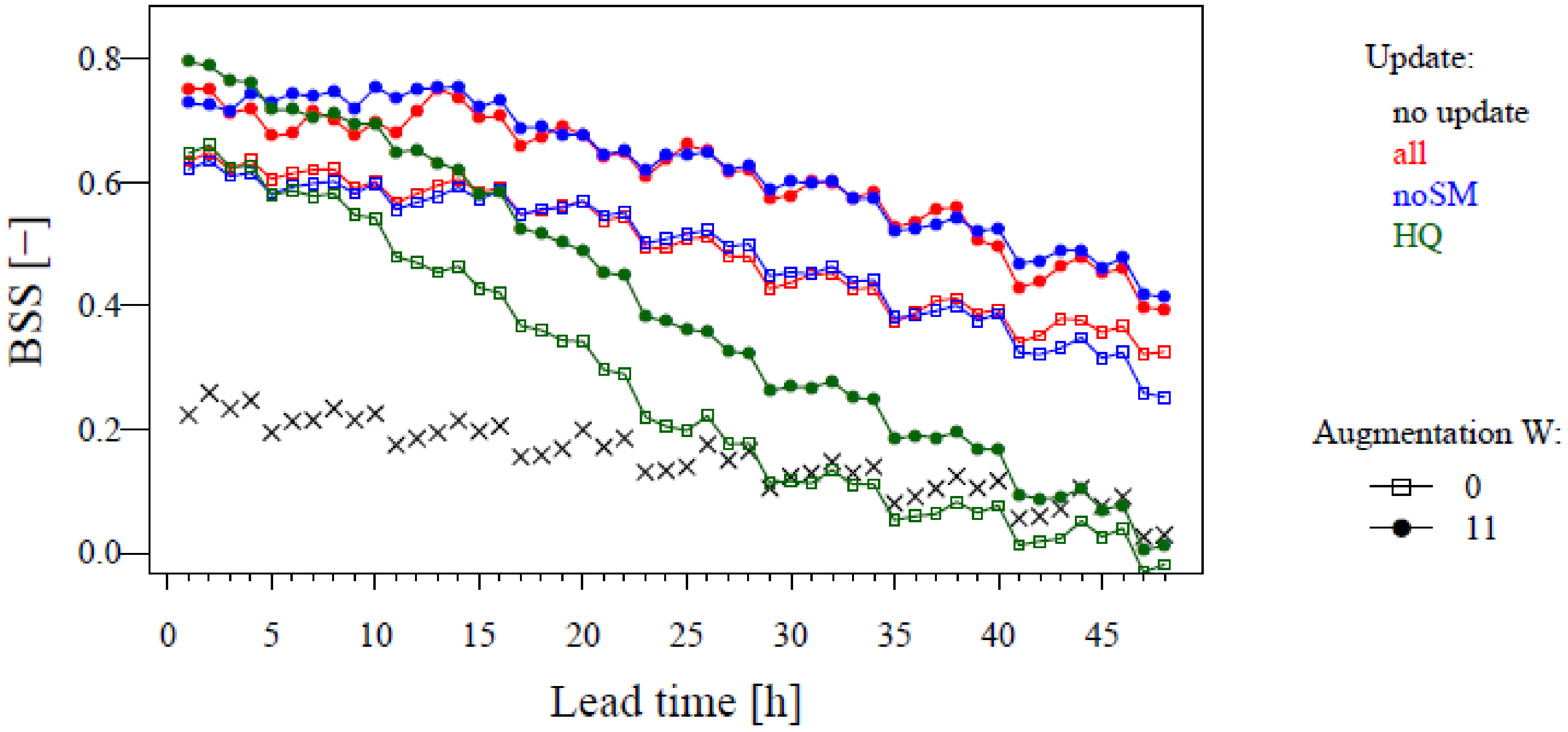
Validation



RMSE
35
30
25
20
15
10
0
5
10
15
20
25
30
35
40
45
Lead time [h]
Update:
no update
all
noSM
HQ
Augmentation W:
0
5
11

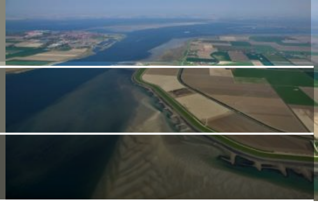


BSS [–]
0.0
0.2
0.4
0.6
0.8
0 5 10 15 20 25 30 35 40 45
Lead time [h]
Update:
no update
all
noSM
HQ
Augmentation W:
0
11

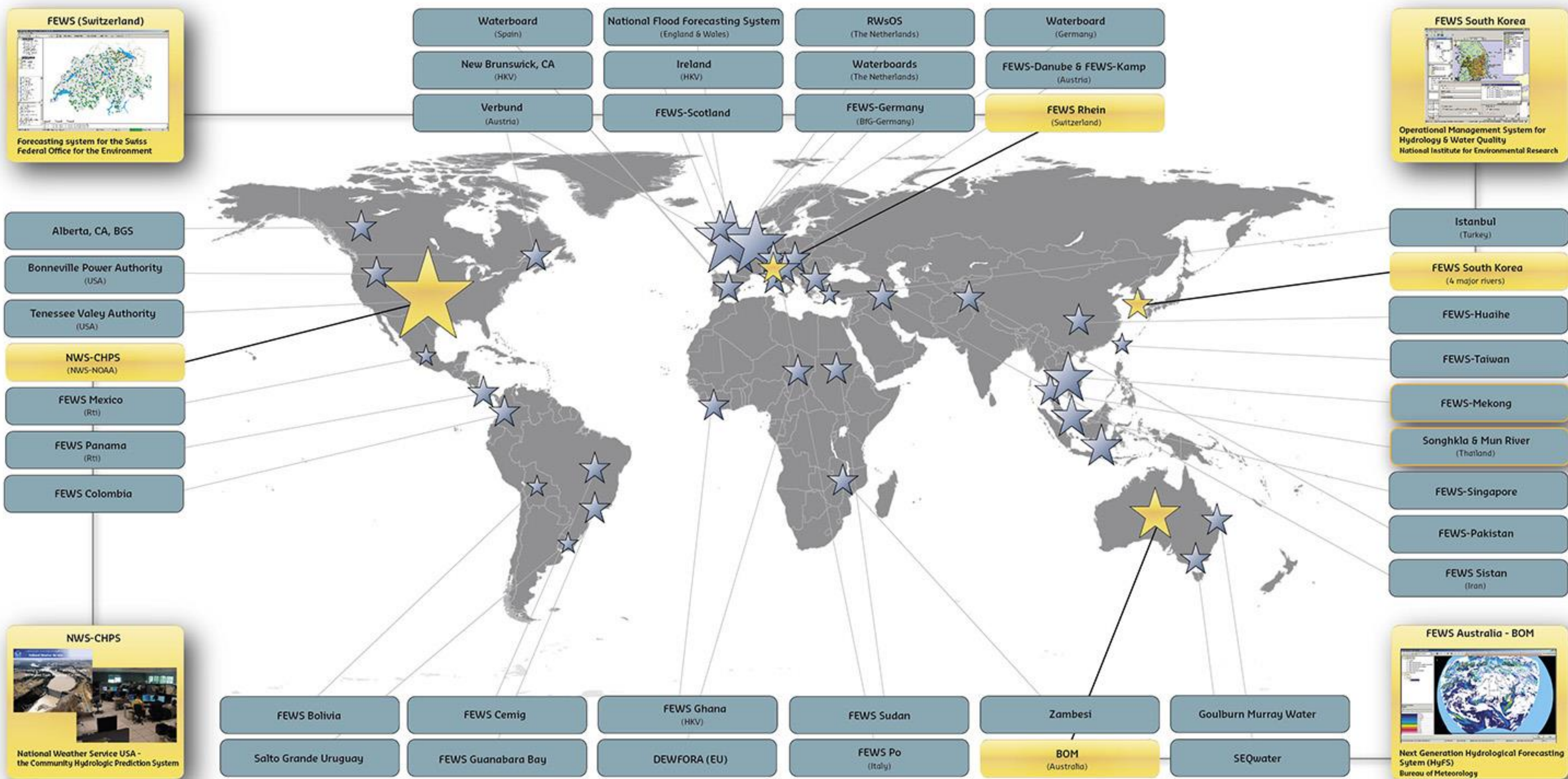
Conclusions AEnKF

- The AEnKF: an effective method for model state updating taking into account more (e.g. all) observations at hardly any additional computational burden;
- Partitioned update scheme: reducing the number of model states using AEnKF can lead to better forecasts of discharge;
- Largest improvements in the forecast accuracy using RMSE were observed for the scenario, when the soil moisture was left out from the analysis (because SM obs. not available);
- Updating only routing states leads to very good performance at time of update, but it deteriorates sharply at longer lead times;
- Keeping the quick catchment response storage (upper zone; UZ) in the model analysis is important especially for longer lead times;

Delft-FEWS worldwide



Delft-FEWS as platform for operational systems worldwide



- Delft-FEWS provides an open shell system for managing forecasting processes and/or handling time series data.
- Delft-FEWS incorporates a wide range of general data handling utilities, while providing an open interface to any external (forecasting) model.
- The modular and highly configurable nature of Delft-FEWS allows it to be used effectively for data storage and retrieval tasks, simple forecasting systems and in highly complex systems utilising a full range of modelling techniques.
- Delft-FEWS can either be deployed in a stand-alone, manually driven environment, or in a fully automated distributed client-server environment.

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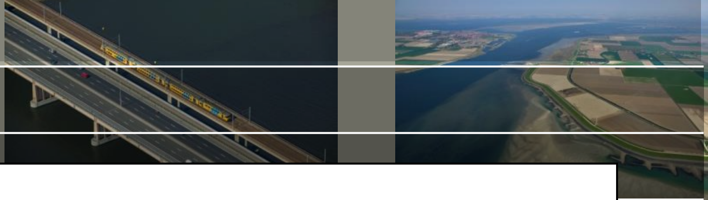
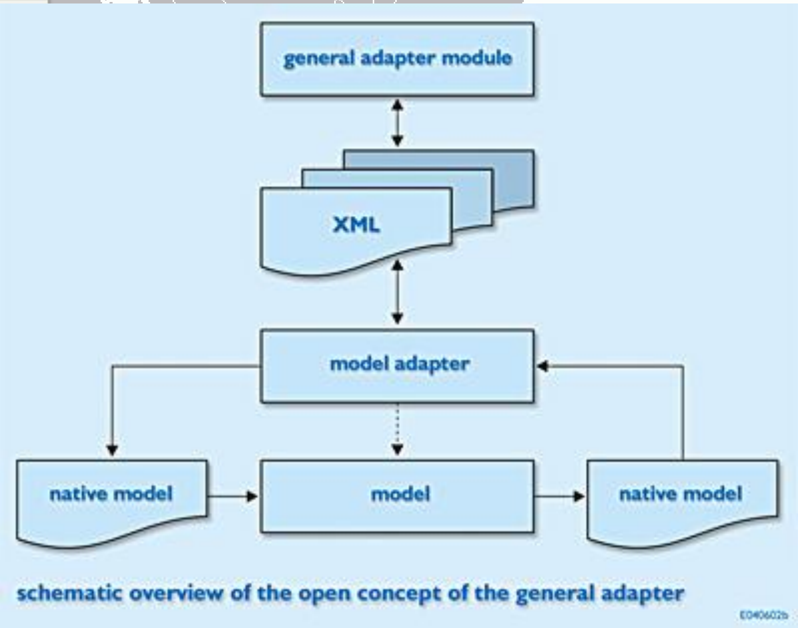
Models coupled



Delft FEWS

Operational Forecasting Platform

Model	Type	Supplier/Owner	Country
ISIS	Hydrodynamics	HR/Halcrow	UK
PDM	Rainfall-Runoff	CEH	UK
TCM	Rainfall-Runoff	CEH	UK
KW	Routing (kinematic wave)	CEH	UK
PACK	Snow Melt	CEH	UK
ARMA	Error Correction	CEH	UK
PRTF	Event Based RR	PlanB	UK
TRITON	Surge propagation/Overtopping	PlanB	UK
STF	Transfer functions	EA	UK
DODO	Routing (layered Muskingum)	EA	UK
MCRM	Rainfall-Runoff	EA	UK
Modflow96/VKD	3D groundwater	Deltares/Adam Taylor	Netherlands/UK
Mike11	Hydrodynamics	DHI	Denmark
NAM	Rainfall-Runoff	DHI	Denmark
LISFLOOD	Distributed Rainfall-Runoff	JRC	Italy
TOPKAPI	Rainfall-Runoff	Univ. of Bologna	Italy
HBV	Rainfall-Runoff (inc snowmelt)	SHMI	Sweden
Vflo	Distributed Rainfall-Runoff	Vieux & Assiciates	USA
SWMM	Urban Rainfall-Runoff	USGS	USA
HEC-RAS	Hydrodynamics	USACE	USA
Snow17	Snow Melt	NWS	USA
SACSM	Rainfall-Runoff	NWS	USA
Unit-H	Unit-Hydrograph	NWS	USA
PRMS	Rainfall-Runoff	Univ. of Karlsruhe	Germany
SynHP	Hydrodynamics	BfG	Germany
SOBEK	Hydrodynamics, Water Quality, RR	Deltares	Netherlands
SOBEK-2d	Linked 1d/2d inundation modelling	Deltares	Netherlands
Sacramento	Rainfall-Runoff	Deltares	Netherlands
RIBASIM	Water distribution + Reservoir	Deltares	Netherlands
REW	Distributed Rainfall-Runoff	Deltares	Netherlands
DELFT3D	2/3D Hydrodynamics/Water quality	Deltares	Netherlands
TWAM	2D Hydrodynamics	PlanB	UK

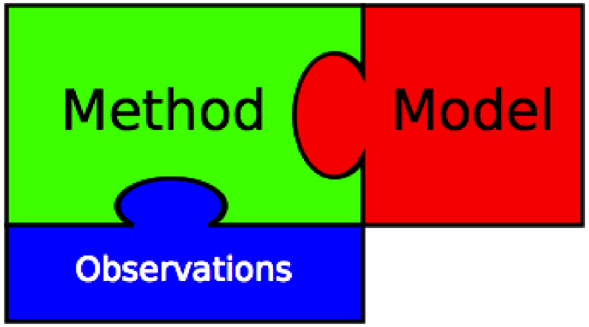


What is OpenDA

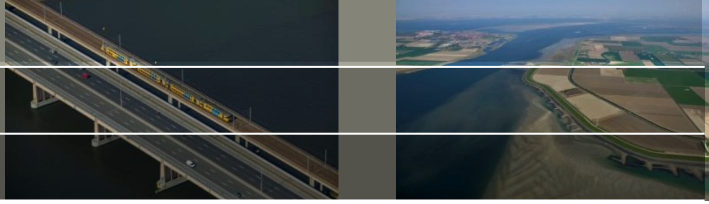
OpenDA is an open source toolbox for data assimilation and parameter calibration in a generic modeling context

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 and calibration methods:
  - ensemble KF, ensemble square root KF, 3DVar, …
  - Dud, Simplex, Powell, Conjugate Gradient, …

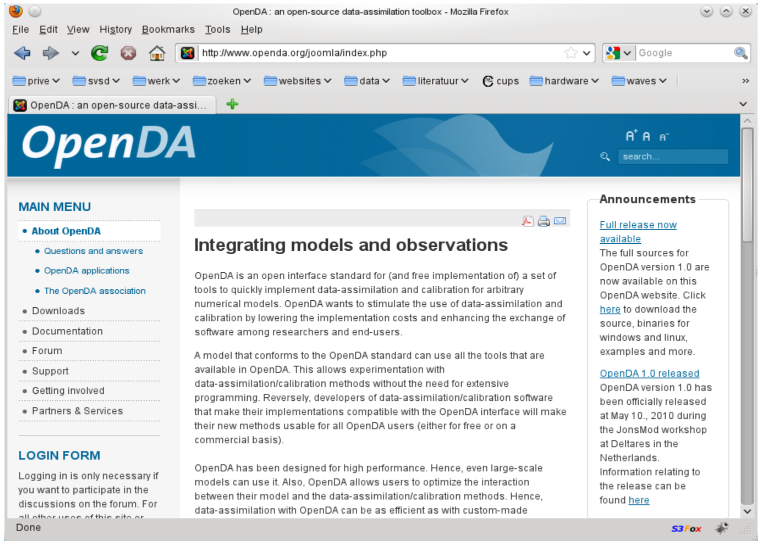


What is OpenDA



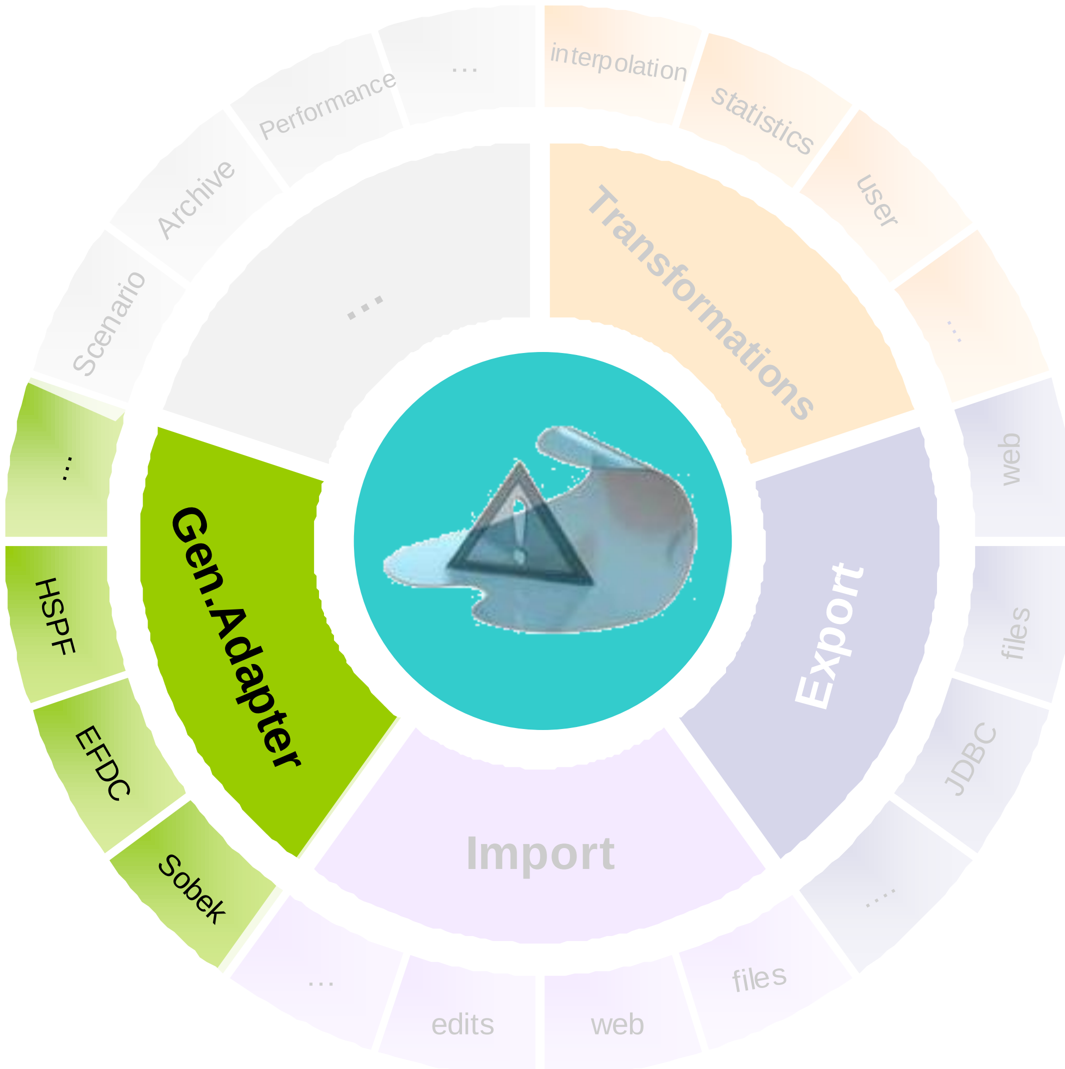
- Open source (LGPL)
- Written in Java / C / Fortran
- Current version: OpenDA 2.1
- Available for Windows, Linux & Mac
- Website: www.openda.org with downloads, documentation, support
- The OpenDA Association:

TU Delft — Deltares Enabling Delta Life — VORtech BV The Scientific Software Engineers



OpenDA

Application in of OpenDA in Delft-FEWS



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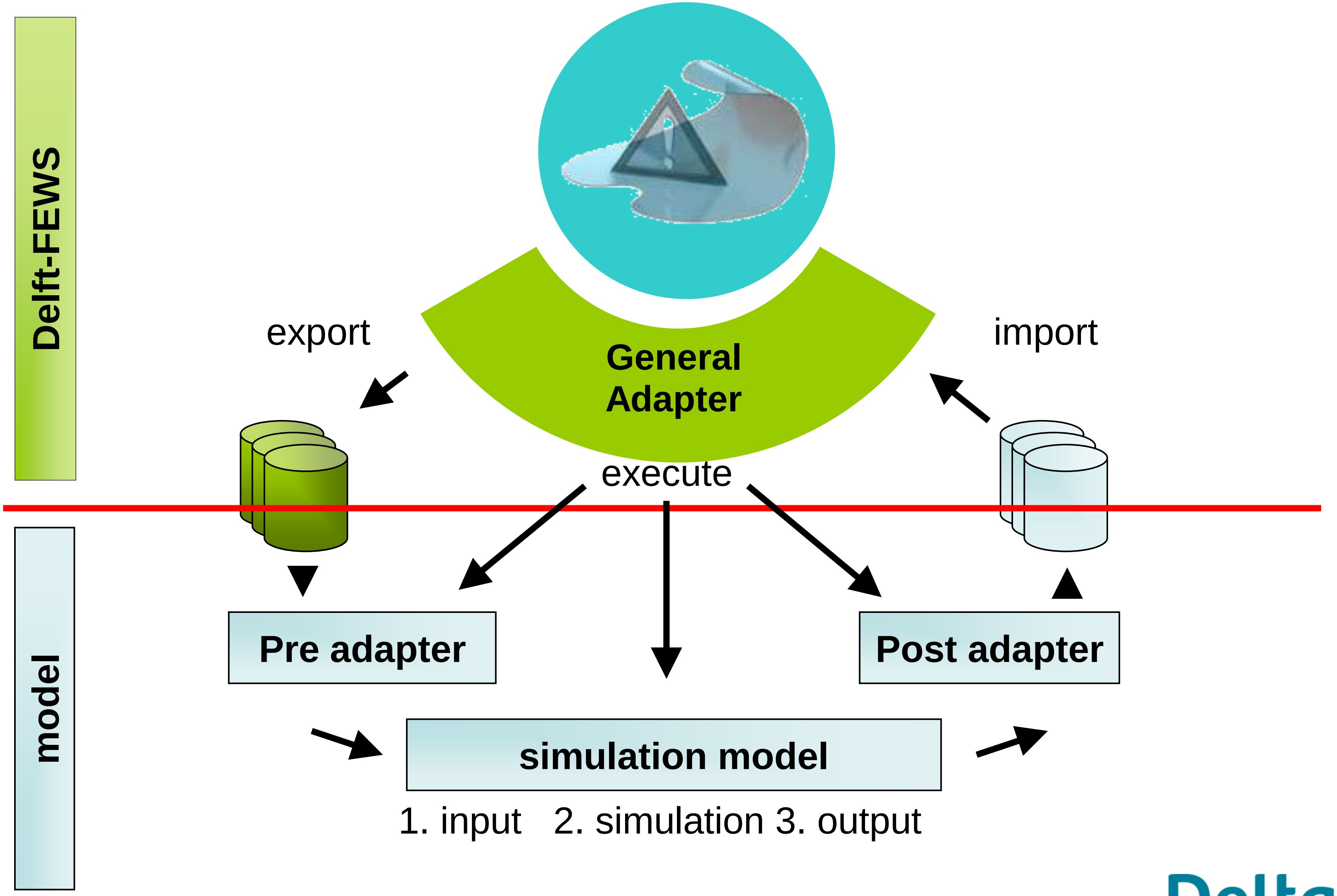
Coupling with models; without openDA



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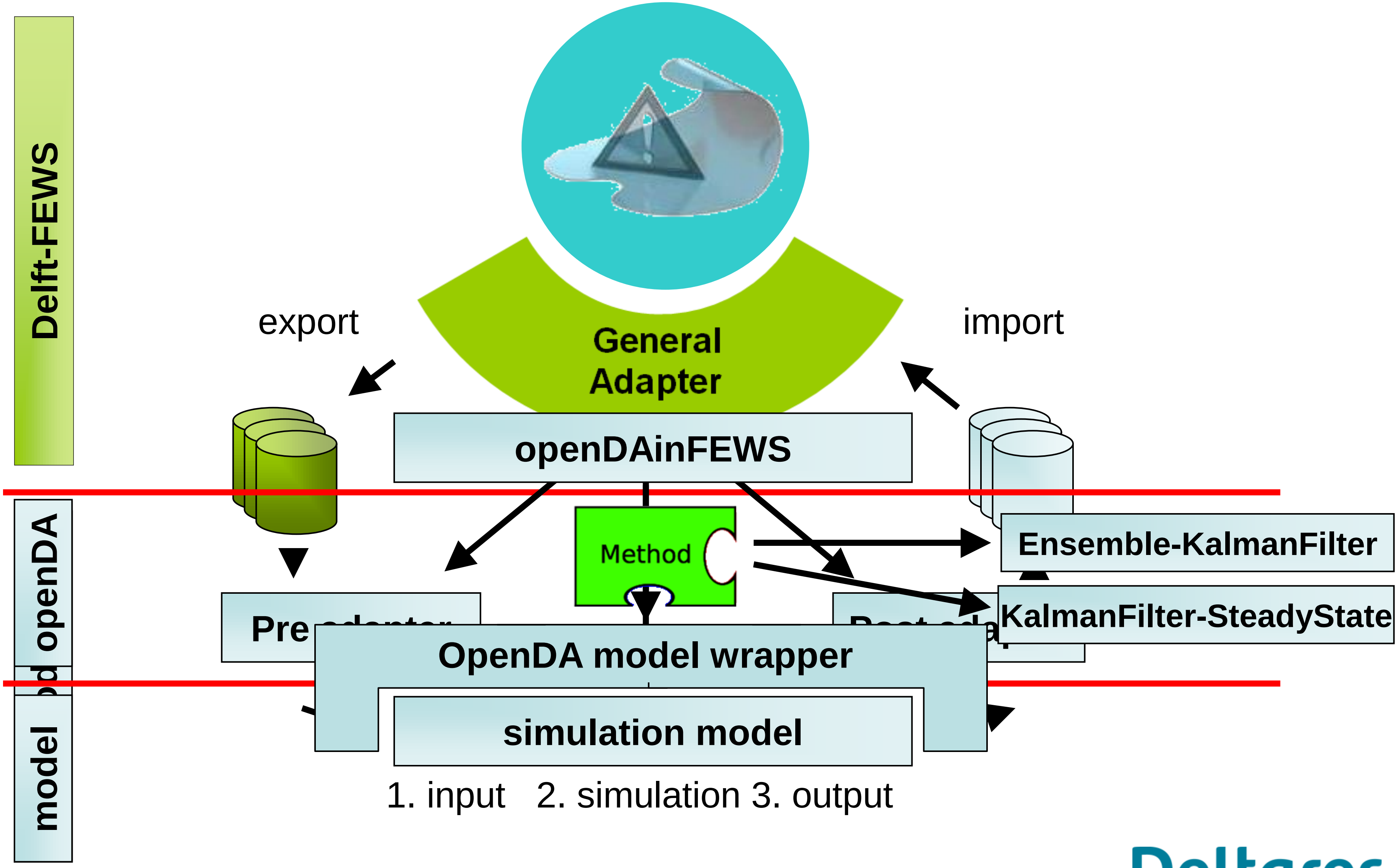
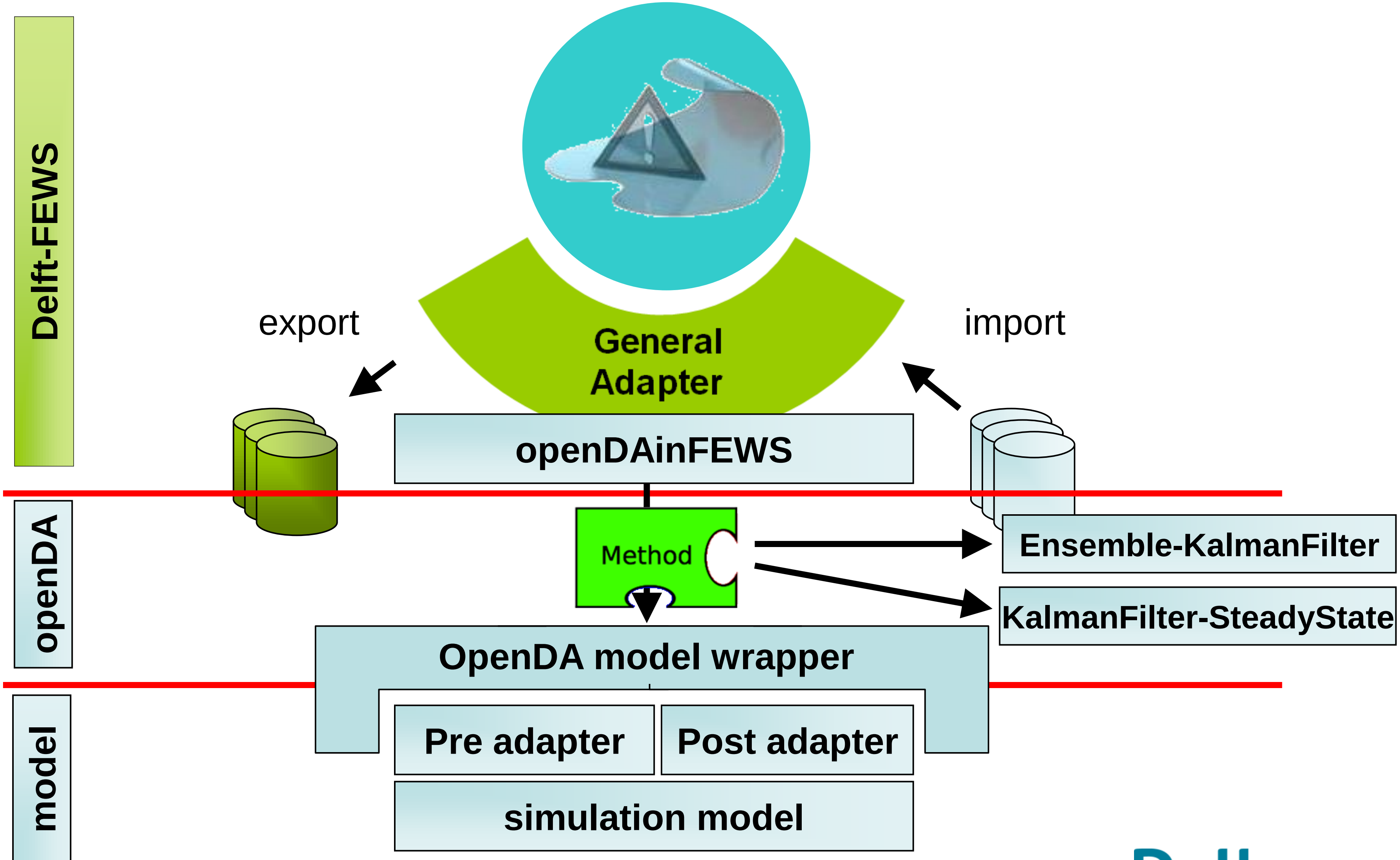
Coupling with models; via openDA blackbox



Coupling with models; via openDA dll (in memory)



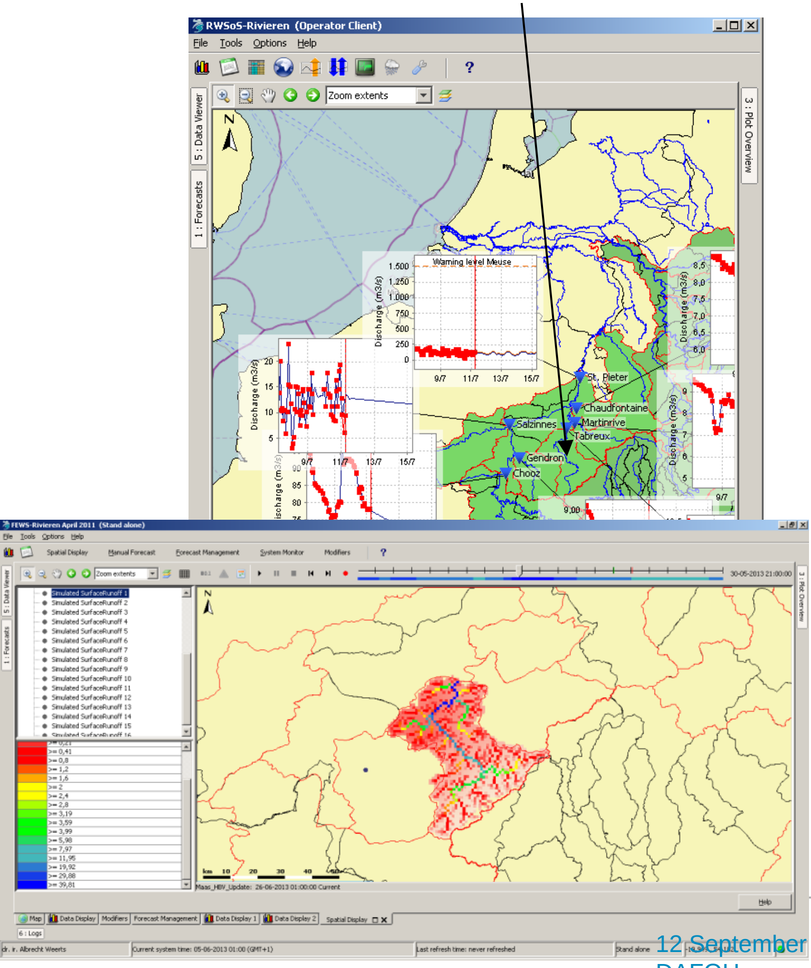
3 examples Delft-FEWS-OpenDA-Model

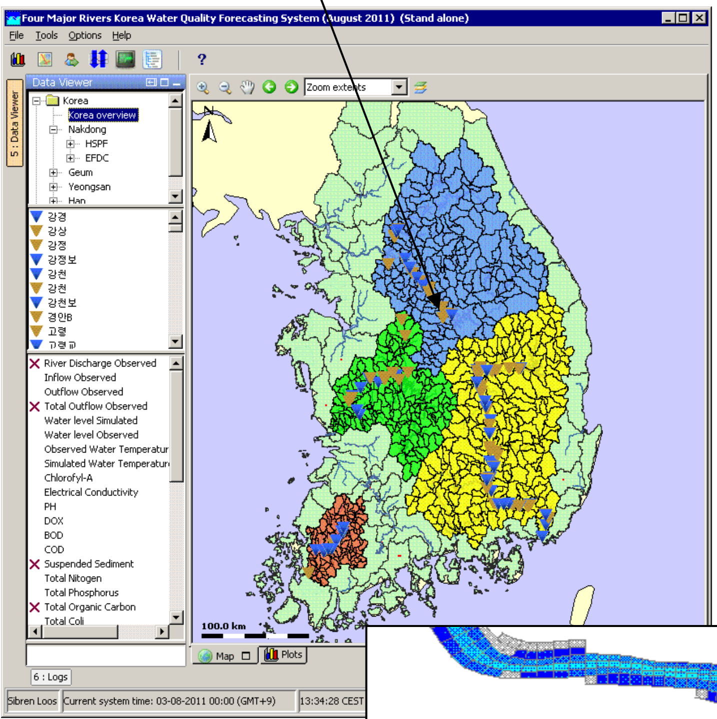
OpenStreams
Distributed Hydrologic Model

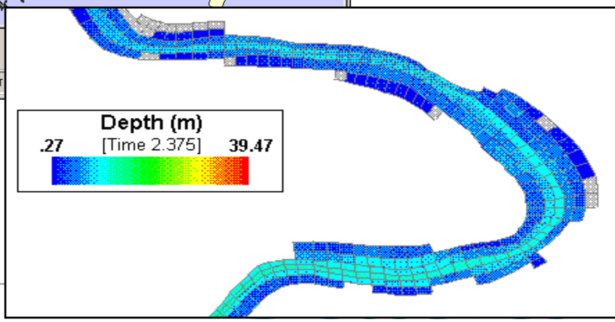
(Belgium – Ourthe catchment)

EFDC 2D Water Quality Model

(Korea – Han River)





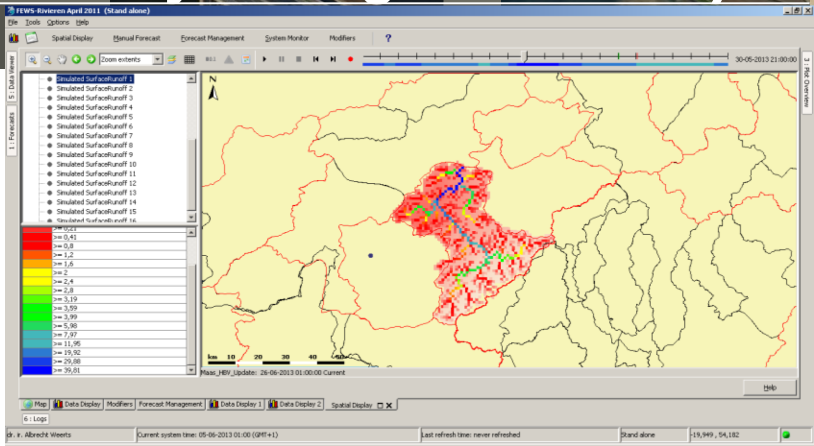


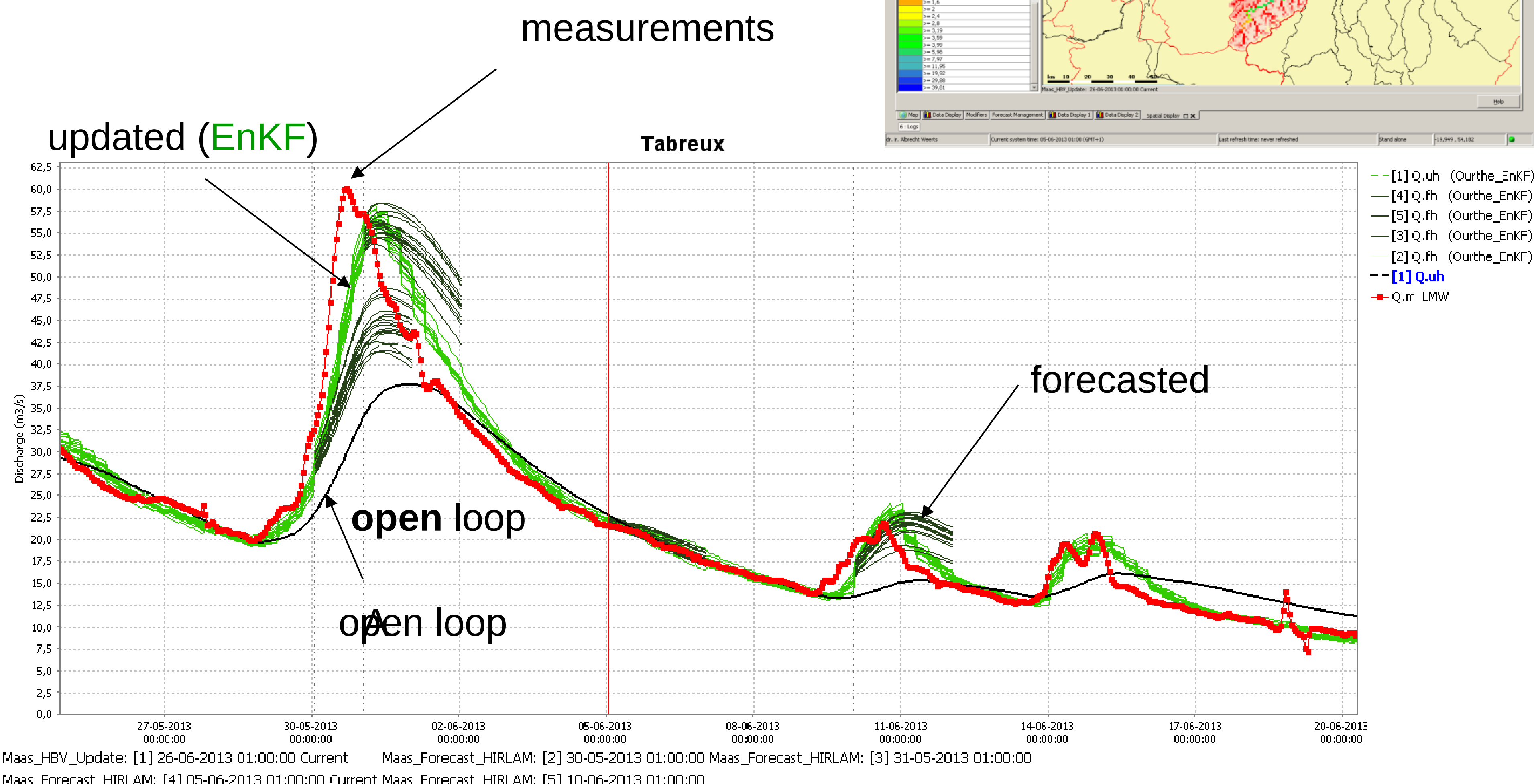
Example OpenStreams (distributed hydrological model)

- Goal: More accurate flood forecasts
- Current Status and setup:
  - HBV-96 OpenStreams model available for the Ourthe (Belgium)
  - Python model OpenDA wrapped via Java Embedded Python (JEP)
  - Pertubations applied to precipitation fields (temporal and spatial correlated if needed)
  - Assimilation of measured discharges at outlet (measurements at intermediate locations is also possible or used as verfication)

- Future:
  - Ready for operational testing in Dutch operational system RWsOS Rivieren, FEWS Taiwan or any other Delft-FEWS flood and water management forecasting system;
  - Next step using satellite observations (e.g. soil moisture, snow, flooded areas etc)

Example OpenStreams (distributed hydrological model)

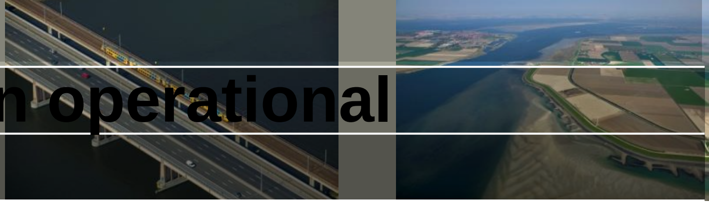




Example EFDC (Environment Fluid Dynamics Code)

- Goal: Improved accuracy Water Quality Forecasts
- Current Status and setup:
  - EFDC 2D-model available for Han River (Korea)
  - Model OpenDA wrapped in memory (.dll/.so)
  - Pertubations applied to radiation, WQ inflows river (temporal correlated)
  - Assimilation of measured WQ parameters (PO_4 or algae) at various locations along the river

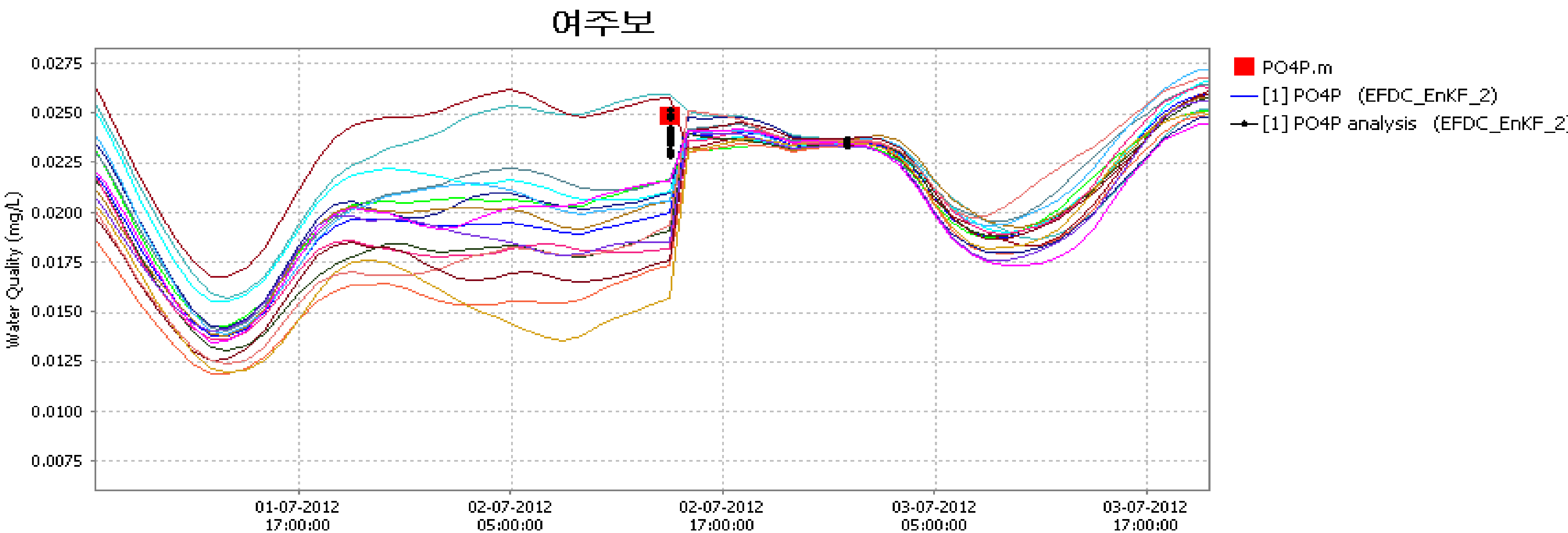
- Future:
  - Ready for operational testing in FEWS NIER or any other FEWS / EFDC users;
  - Possible use satellite measurements algae blooms, water temperature;

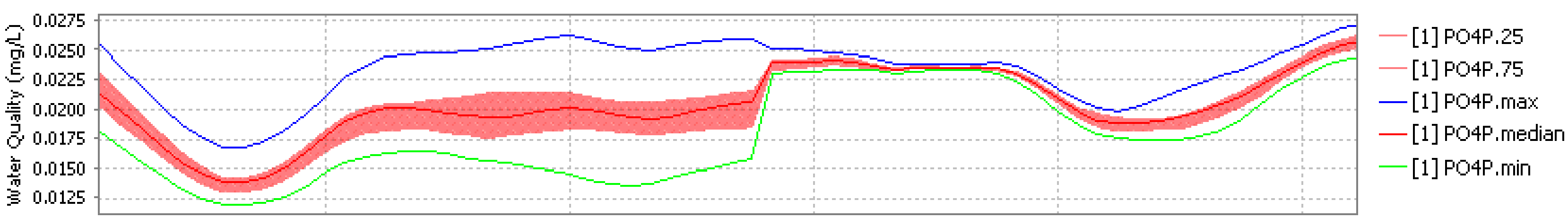


Example EFDC: Implementation in an operational forecasting system

Observation, Forecast, Analysis and Ensemble statistics

Real-time data assimilation of PO_4





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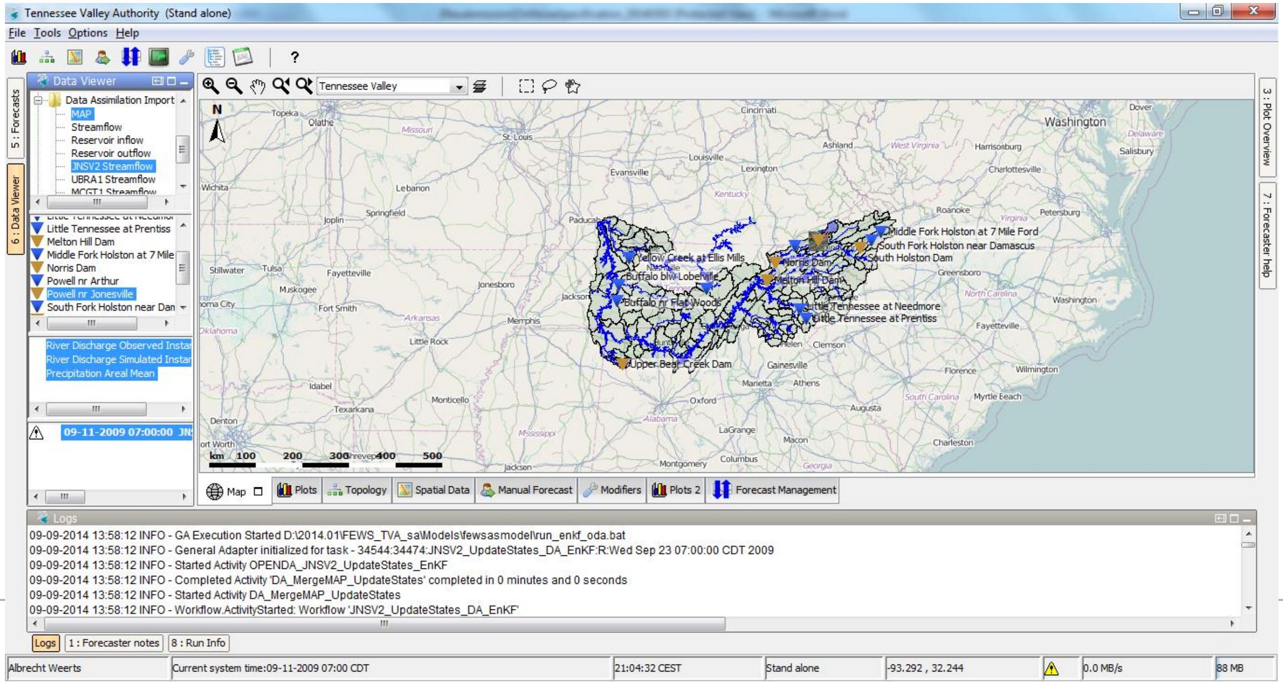
3rd example is work in progress…

Together with Riverside, NCAR, Deltares USA investigate the feasibility of guided (ensemble based) DA for operational forecasting in the US Tennessee River basin

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 <u>parallel</u> 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 will be presented at AGU 2014;

Concluding remarks

- A lot of research has been conducted the last couple of years on the topic of Hydrologic Ensemble DA;

- Operational ensemble based (guided) DA is becoming feasible and the obstacles for usage are only 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;