ECMWF / H-SAF and HEPEX workshops on coupled hydrology

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Assimilating H-SAF Products (Snow coverage, Snow Water Equivalent and Soil Moisture) into a Conceptual Rainfall-Runoff Model

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Objectives

- Design and implementation of a generic framework for Data Assimilation of hydrological models in combination with H-SAF remote sensing products

- Application of the framework for validating H-SAF remote sensing data regarding the improvement of the lead-time accuracy of forecasts for test sites in Germany and Turkey

- Potential knowledge transfer to the other H-SAF partners for enabling further research

Introduction

- Data Assimilation by Moving Horizon Estimation (MHE)
  - Optimization-based, variational assimilation approach is very flexible in terms of data outliers, missing data, or data provided at non-equidistant time steps
  - Handles large time lags between forcing and response
  - Flexible formulations for defining the norms indicating agreement of observed and simulated values, etc.

- Hydrological Modeling by HBV and SRM models
  - Dedicated implementation including an adjoint model (for computing first-order derivatives)
  - Dedicated extensions for overruling model states, aggregating SWE from SP and WC, etc.

Introduction – Technical Framework

- RTC-Tools / Open Streams Library
  - Dedicated implementation of the HBV and SRM models (simulation / adjoint mode) as well as many other models
  - Embedded IPOPT optimizer for the data assimilation by MHE
  - Interfaces to Delft-FEWS, OpenMI, OpenDA, GAMS, Matlab
  - ANSI C++ implementation
  - Open Source under GPL2
  - Development by Deltares, University of Duisburg-Essen, Fraunhofer IOSB-AST

- Data-Model Integration Platform (Delft-FEWS)
  - Commonly used operational forecasting platform for hydrological products (UK Environmental Agency, US National Weather Service, Swiss Federal Office for the Environment , German BfG, etc.)
  - Integration of data feeds, data processing and models into hindcast experiments
  - Freely available for end users

Introduction – Technical Framework

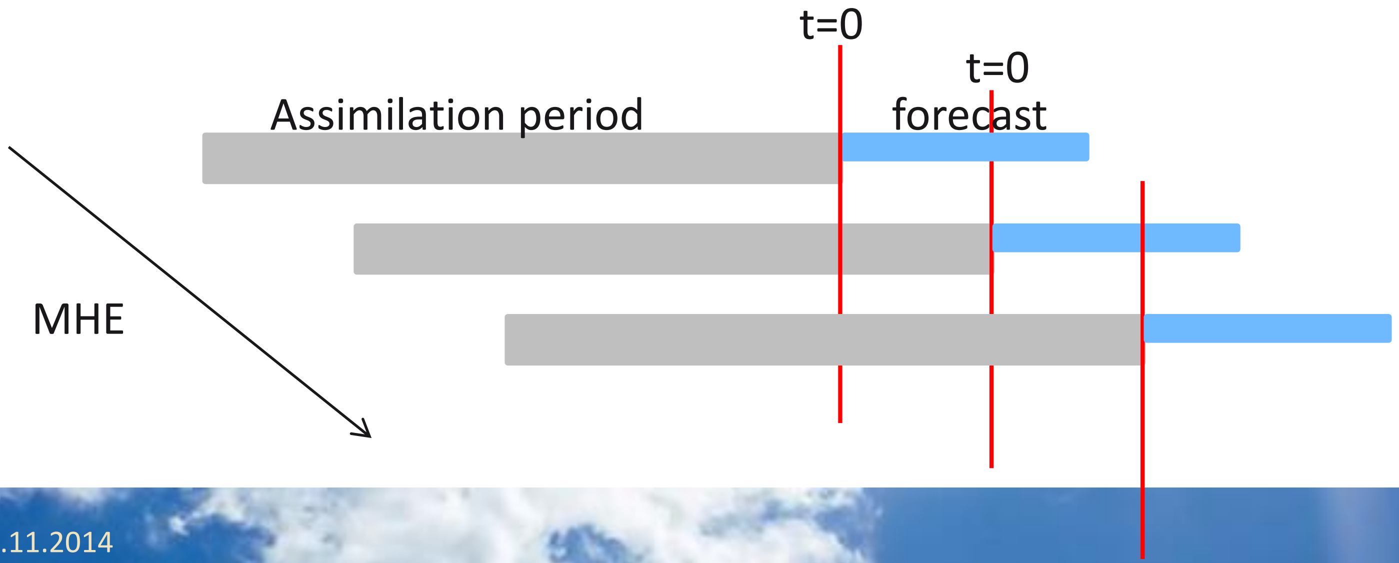
Modular approach, exchangeable components, commonly used interfaces, high maturity level, free access:

Data-Model Integration	Delft-FEWS	Alternatives: - Dedicated implementation
↕ Delft-FEWS PI-XML interface		
Data Assimilation	Variational MHE approach in RTC-Tools	Alternatives: - OpenDA (openda.org) - Matlab prototype
↕		
Hydrological Model	HBV, SRM with simulation/adjoint mode in RTC-Tools	Alternatives: - Matlab prototype - Black-box models (with Kalman Filter type DA)

Introduction – Variational Data Assimilation

Variational data assimilation method based on Moving Horizon Estimation (MHE):

- creates a simulation over an assimilation period by a model,
- mathematically expresses the assimilation of simulated variables compared with observations within a cost function,
- minimizes this cost function by an optimization algorithm,
- apply the assimilated states as input for the forecast
- repeats the procedure for the next time step



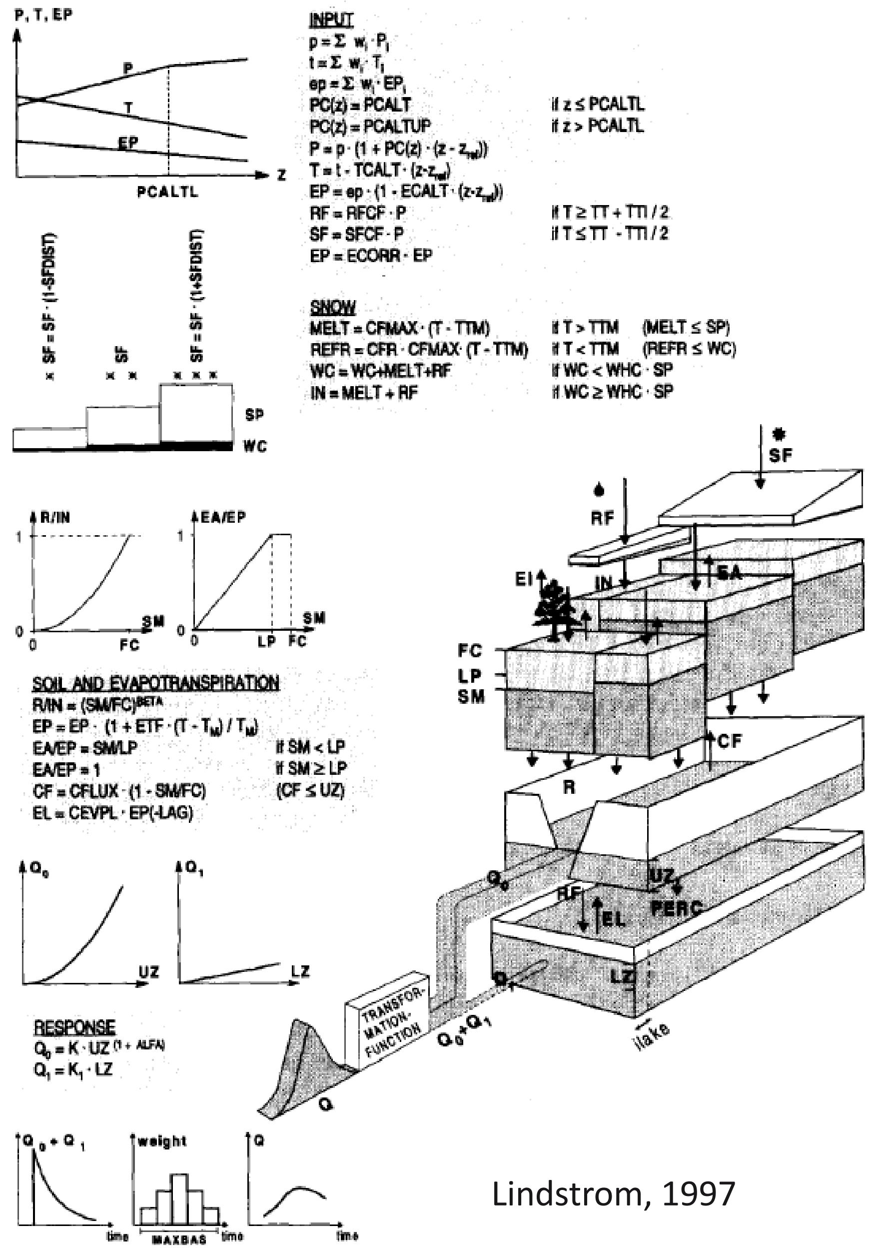
Methodology – Hydrological Model

HBV model as a conceptual hydrological model as internal model in the MHE

Temperature, precipitation and evapotranspiration as main inputs

Among state variables:

- soil moisture
- upper zone
- lower zone



Lindstrom, 1997

Methodology – Variational Data Assimilation

The implementation of the HBV model follows:

Disturbance/forcing vector

states → $$x^k = f(x^{k-1}, d^k, u^k)$$

output variable → $$y^k = g(x^k, d^k, v^k)$$

noise vectors

Linear and non-linear functions representing the HBV model

The Moving Horizon Estimation (MHE) for a forecast *k=0* over an assimilation period *k=[-N+1,0]* is defined as:

Observations

$$\min_{u,v} \sum_{k=-N+1}^{0} \left[w_x \left\| \hat{x}^k - x^k(u) \right\| + w_y \left\| \hat{y}^k - y^k(u,v) \right\| + w_u \left\| u^k \right\| + w_v \left\| v^k \right\| \right]$$

⟸ Objective function

$$\text{subject to} \quad u_L \le u^k \le u_U$$

$$\mathrm{v}_L \le v^k \le v_U$$

⟸ Hard constraints

* Adjoint models are required for the optimization to run more efficiently

Methodology – Variational Data Assimilation

Variables and objective function terms in the MHE

Variable		Objective Function Term
Model Inputs	Precipitation (P)	$w_P(\underline{\Delta P^k})^2$
	Temperature (T)	$w_T(\underline{\Delta T^k})^2$
Model States	Snow Water Equivalent ($SWE = SP + WC$)	$w_{SWE}(\hat{s}_{SWE}^k - s_{SWE}^k)^2$
	Soil Moisture (SM)	$w_{SM}(\hat{s}_{SM}^k - s_{SM}^k)^2 + w_{\Delta SM}(\underline{\Delta s_{SM}^k})^2$
	Upper Zone Storage (UZ)	$w_{\Delta UZ}(\underline{\Delta s_{UZ}^k})^2$
	Lower Zone Storage (LZ)	$w_{\Delta LZ}(\underline{\Delta s_{LZ}^k})^2$
Model Outputs	Snow Covered Area (SCA)	$w_Q(\hat{A}_{SCA}^k - A_{SCA}^k)^2$
	Discharge (Q)	$w_Q(\hat{Q}^k - Q^k)^2$

Description of Test Sites

Nahe catchment, Germany

mean average discharge: 15.8 m^3/s

area: 1468 km^2

60% covered by forest

elevation between 150 and 800 m (ASL)

Main catchment, Germany

mean average discharge: 30.1 m^3/s

area: 2419 km^2

40% covered by forest

elevation between 250 and 1100 m (ASL)

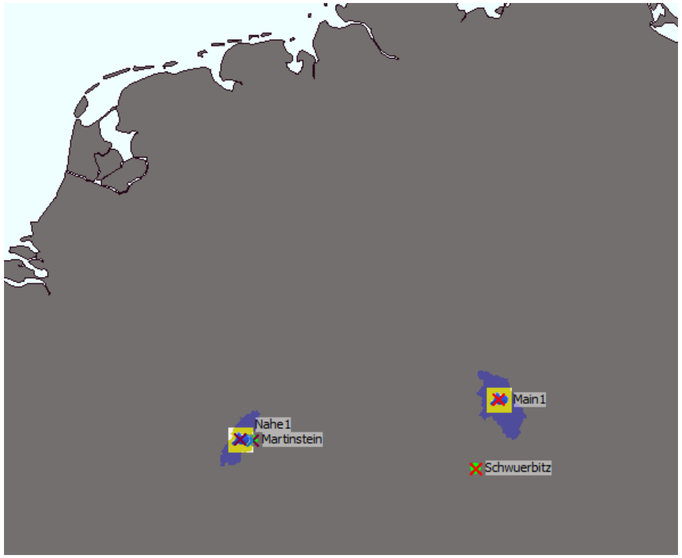
Karasu catchment, Turkey

mean average discharge: 84.4 m^3/s

area: 10275 km^2

covered by pasture, shrub and grass

elevation between 1125 and 3487 m (ASL)



HBV Model for Each Case

- 7 elevation zones and 2 land use for Nahe1
- 7 elevation zones for fields and 9 for forrests for Main1
- 5 elevation zones for Karasu

Basin	Av. Flow	Calibration				Validation			
	Q	BIAS	RMSE	R2	NSE	BIAS	RMSE	R2	NSE
	[m^3/s]	[m^3/s]	[m^3/s]	[-]	[-]	[m^3/s]	[m^3/s]	[-]	[-]
Karasu	85.14	-1.49	33.22	0.840	0.840	-6.69	34.07	0.75	0.74
Main1	31.05	1.37	11.26	0.912	0.909	-1.22	14.21	0.85	0.85
Nahe1	15.65	-0.43	6.858	0.917	0.917	-1.72	8.14	0.87	0.87

- German catchments have a calibration period of 44 years (1962-2006) and 5 years of validation (2007-2012)
- Calibration for Karasu was done for 7 years (2001-2008) and 3 years of validation (2009-2012)
- Availability of data for Turkish basin is limited
- Notice that validation is already better for the German catchments

Experiments

1. Model Potential for Data Assimilation
   Does the model structure enables an improvement of simulated runoff by data assimilation?

2. Potential benefit of H-SAF products?
   What improvements can be achieved under assumption of 'perfect' data products for snow, soil moisture etc.?

3. Practical benefit of H-SAF products?
   What improvement is achieved by the use of the H-SAF products?

1st Experiment

WaWi UDE

Assessment of maximum assimilation potential and model response

- Large variation of variables
- High emphasis on minimizing streamflow deviation

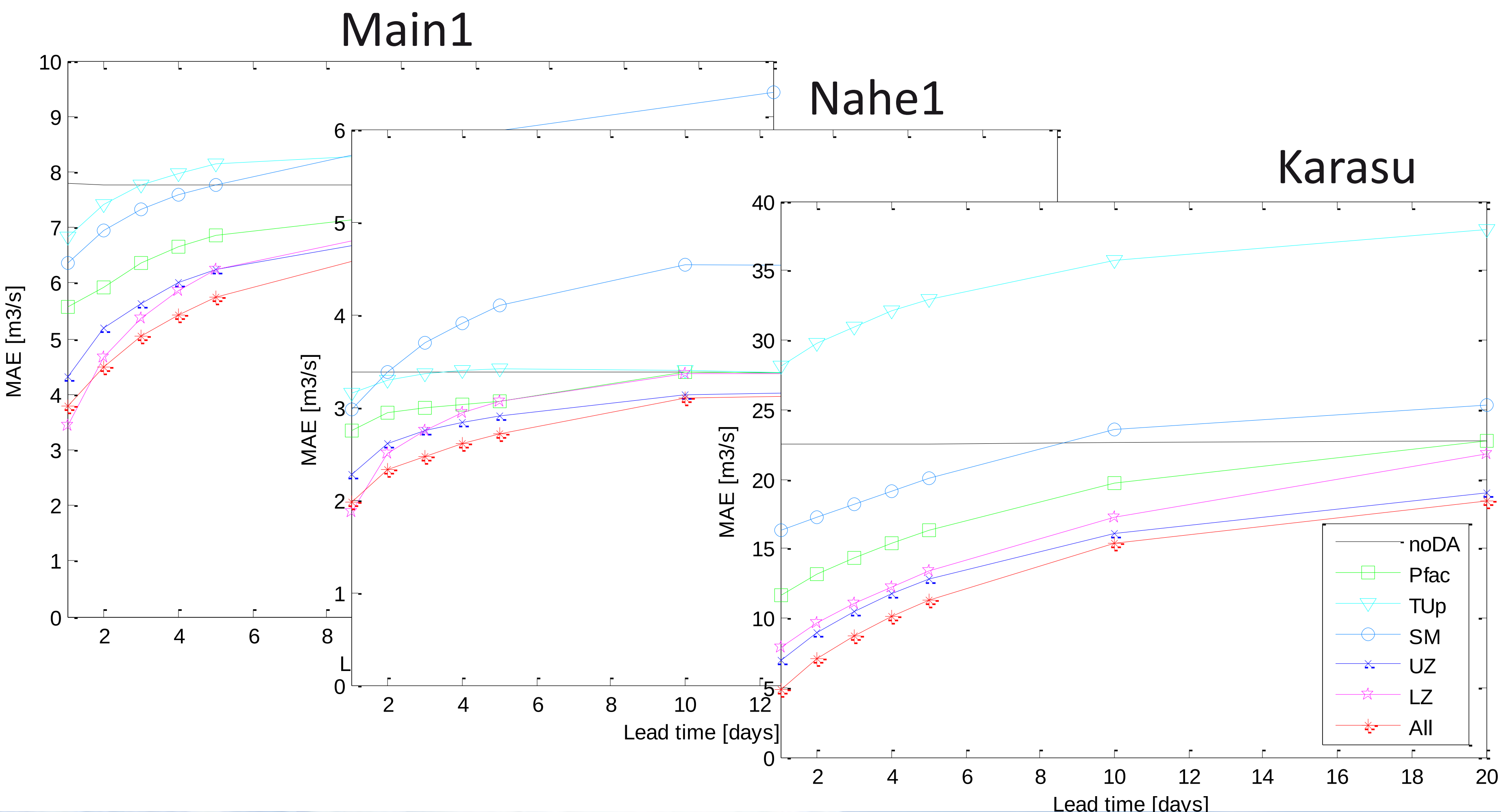
Basin	Mean flow [m³/s]	Perf. Ind.	Without DA	DA (ΔP)	DA (ΔT)	DA (ΔSM)	DA (ΔUZ)	DA (ΔLZ)	DA (ALL)
Karasu	84.99	BIAS	-1.49	-1.51	-2.82	-0.10	0.77	1.34	-0.06
		RMSE	33.22	19.05	15.61	16.33	9.38	21.32	3.58
		R2	0.843	0.948	0.966	0.961	0.987	0.934	0.998
		NSE	0.839	0.947	0.965	0.961	0.987	0.934	0.998
Main1	31.05	BIAS	1.372	0.369	1.227	-0.853	0.401	0.2	0.038
		RMSE	11.261	6.358	7.177	8.393	4.425	5.813	1.729
		R2	0.912	0.971	0.964	0.951	0.986	0.976	0.998
		NSE	0.909	0.971	0.963	0.950	0.986	0.976	0.998
Nahe1	15.65	BIAS	-0.431	-0.183	-0.36	-0.815	0.077	0.11	-0.008
		RMSE	6.858	3.467	4.905	5.117	1.735	3.395	1.093
		R2	0.917	0.979	0.958	0.956	0.995	0.980	0.998
		NSE	0.917	0.979	0.958	0.954	0.995	0.980	0.998

1st Experiment - Results

- The model structure of the conceptual HBV model allows extensive modifications by the data assimilation procedure
- Modifications of states which are closer to the response lead to better agreements between observed and simulated runoff, but do not have an impact on upstream model components
- Data assimilation procedure works well from a technical perspective, even for a long assimilation horizons of up to 40 years in a single assimilation run
- Very high computational performance enables the operational application of the approach and supports the execution of hindcast experiments

1st Experiment - Model Potential for DA

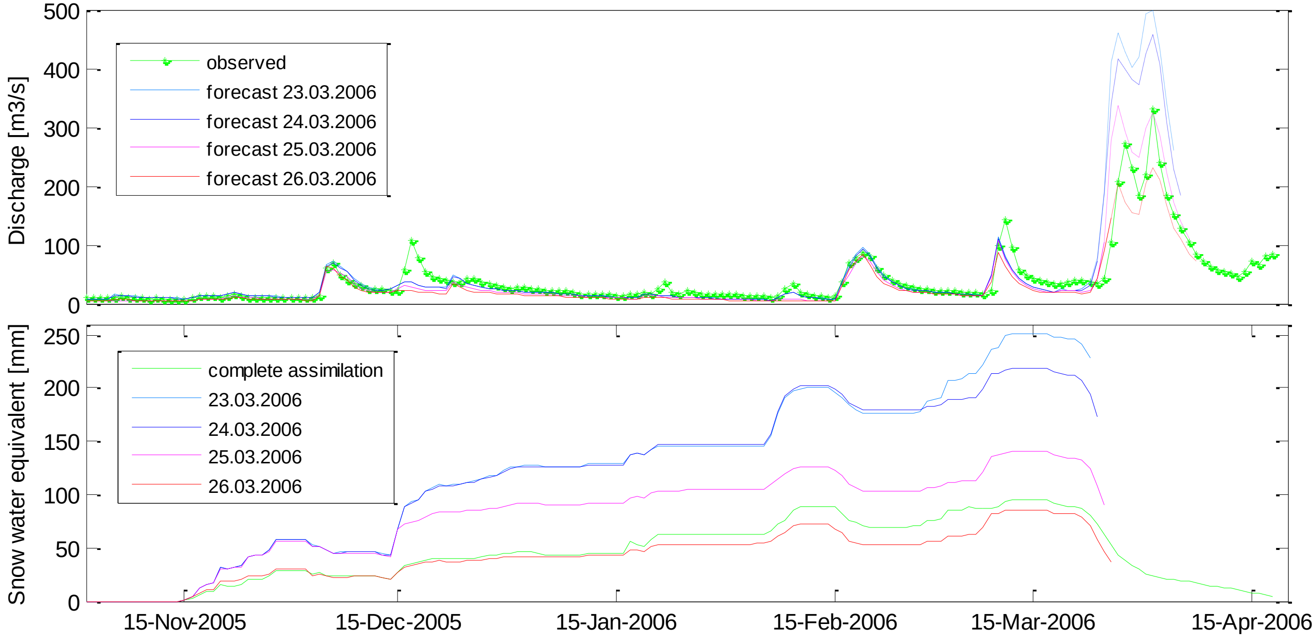
Lead time performance by assimilating discharge:



2nd Experiment

Potential benefit of HSAF products

- Generate perfect time series of soil moisture (SM), snow coverage (SCA), and snow water equivalent (SWE) using observed data (P, T, EPW)
- Include random noise to input data (precipitation, temperature)
- Agreement is given to SM, SCA and SWE in objective function (excluding the contribution of streamflow)



Assimilating discharge

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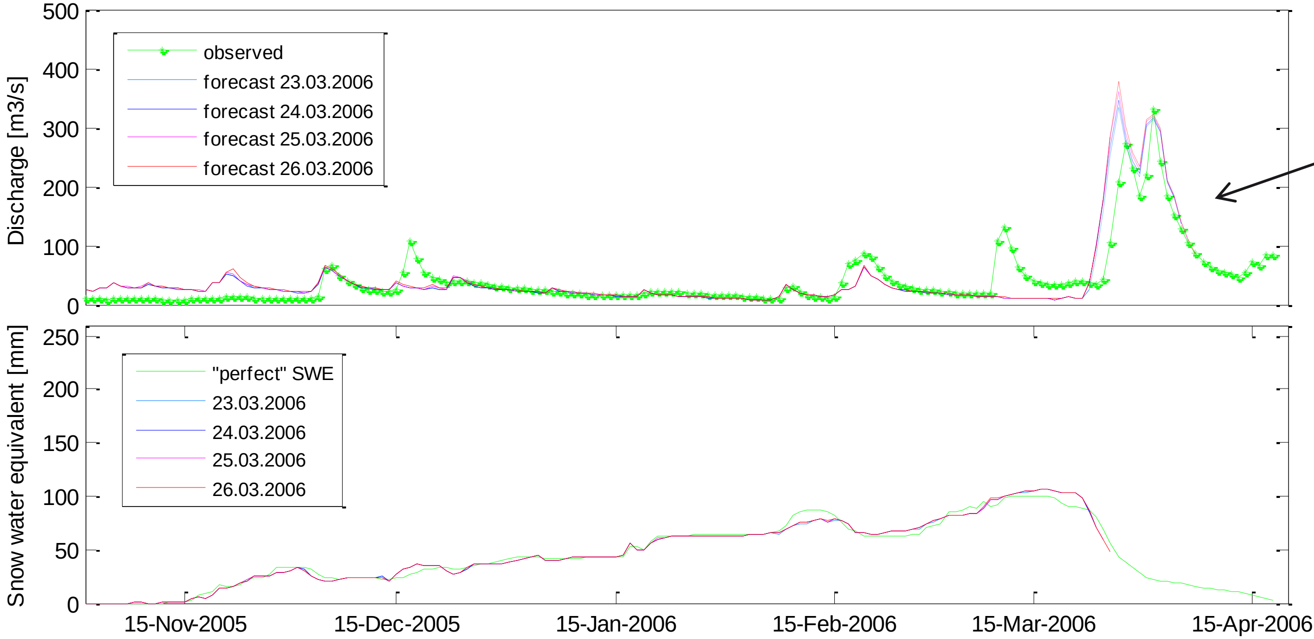


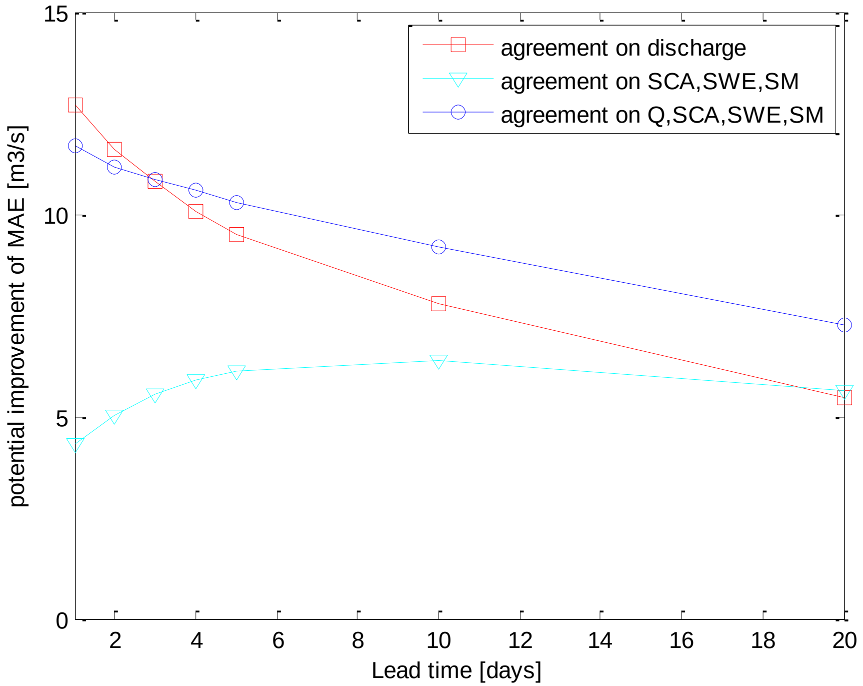
Significant improvement over forecast

Assimilating soil moisture

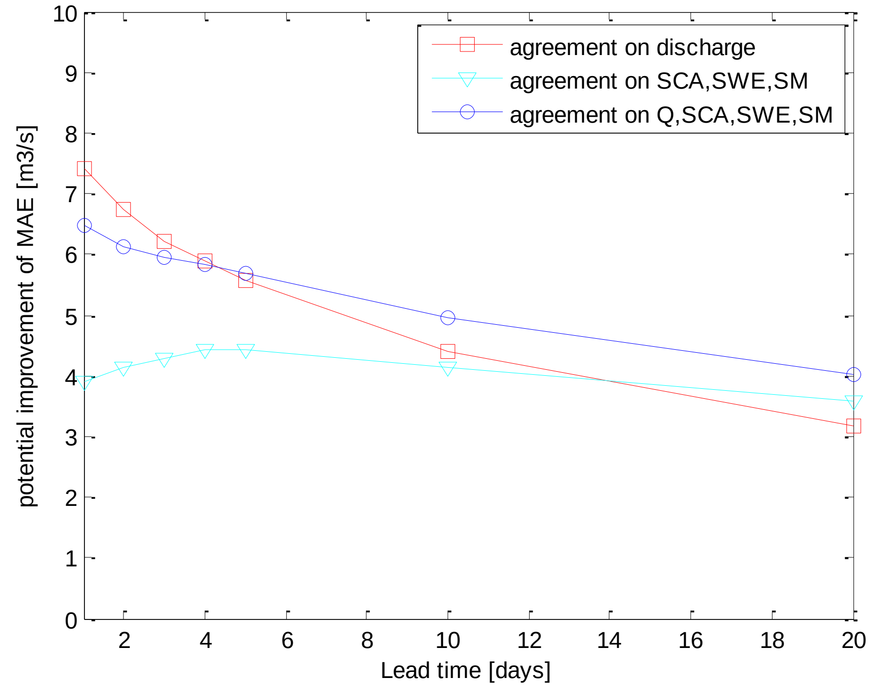
2nd Experiment

We run hindcasts during our validation period

Main1



Nahe1

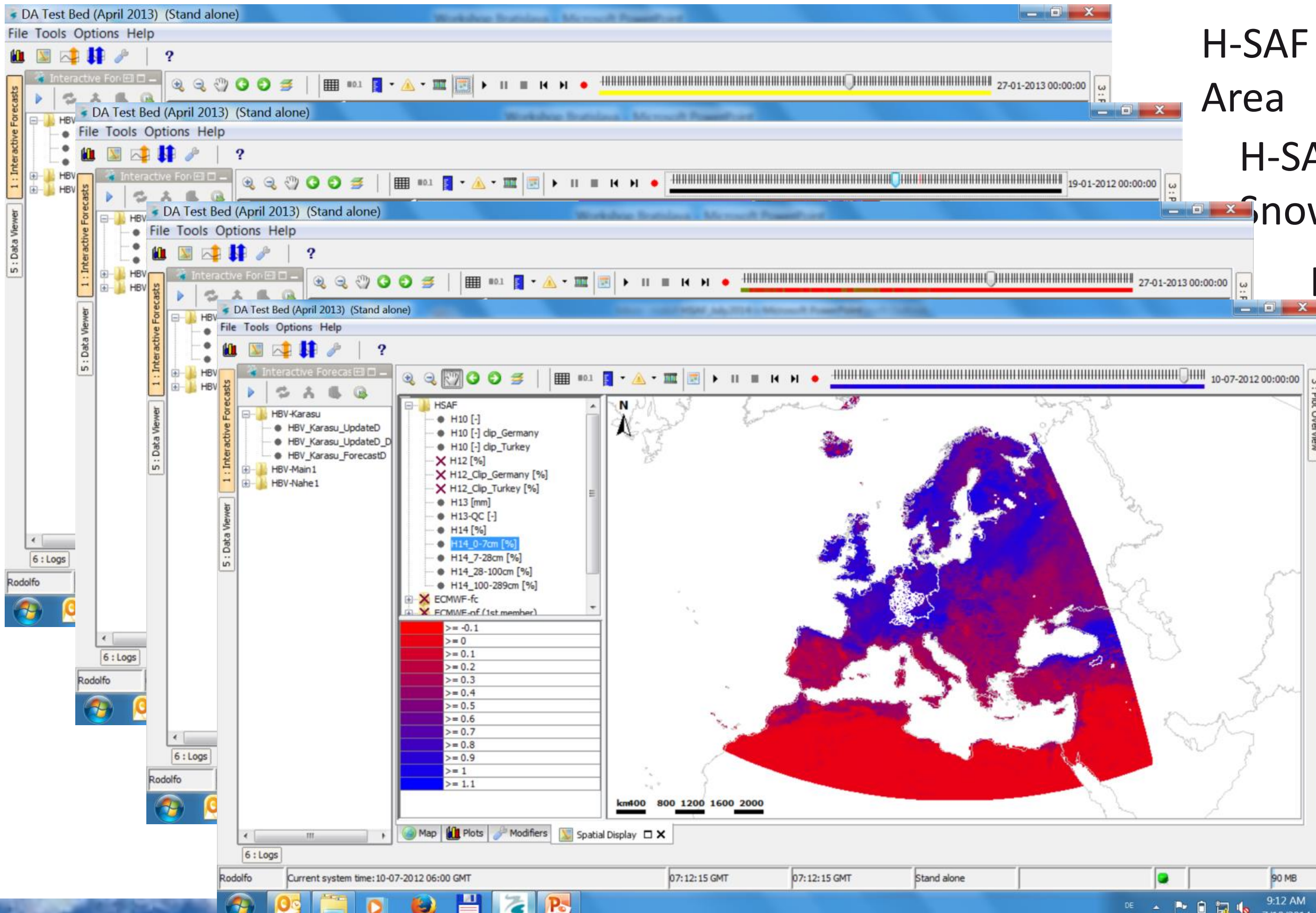


small improvements respect to assimilation of discharge even having perfect time series. The procedure will lead to a better representation of observed SWE and therefore better estimate of future SWE (3rd exper.)

3rd Experiment

Using real data from HSAF observations

- Implementation of available products into the assimilation procedure



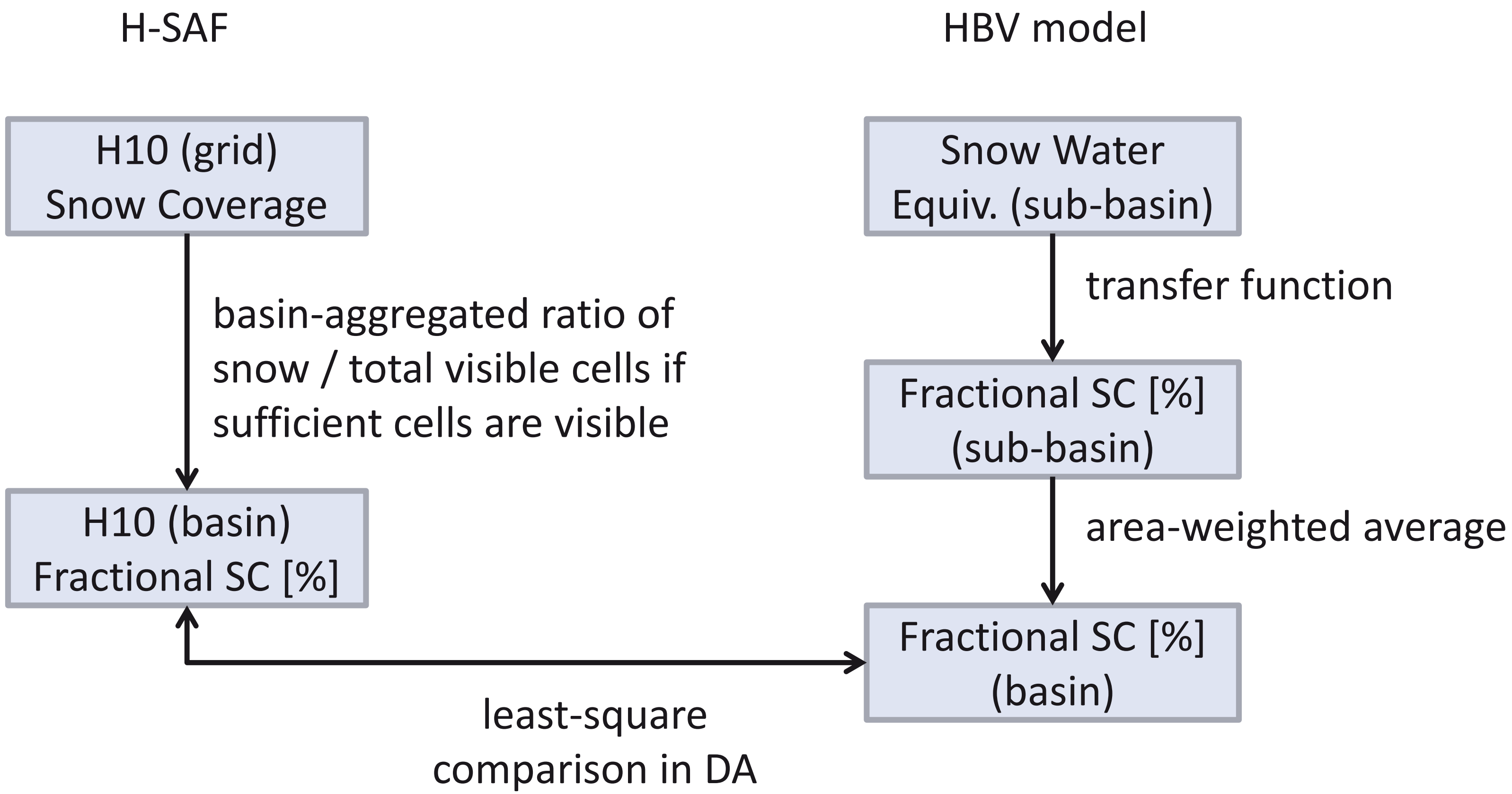
H-SAF H10: Snow Covered Area

H-SAF H12: Fractional Snow Coverage

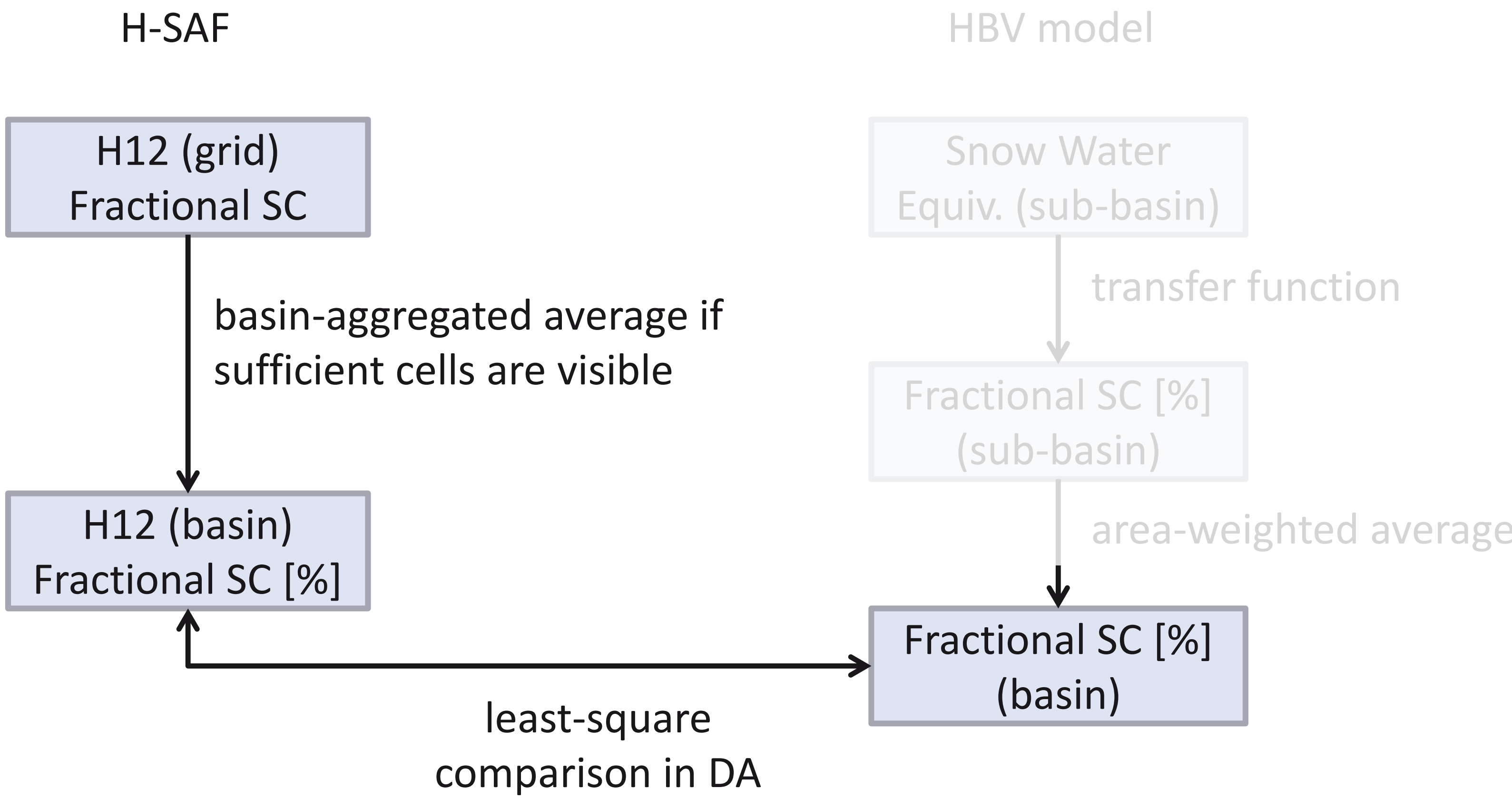
H-SAF H13: Snow Water Equivalent

H-SAF H14: Soil Moisture

3rd Experiment – Procedures by Product



3rd Experiment – Procedures by Product



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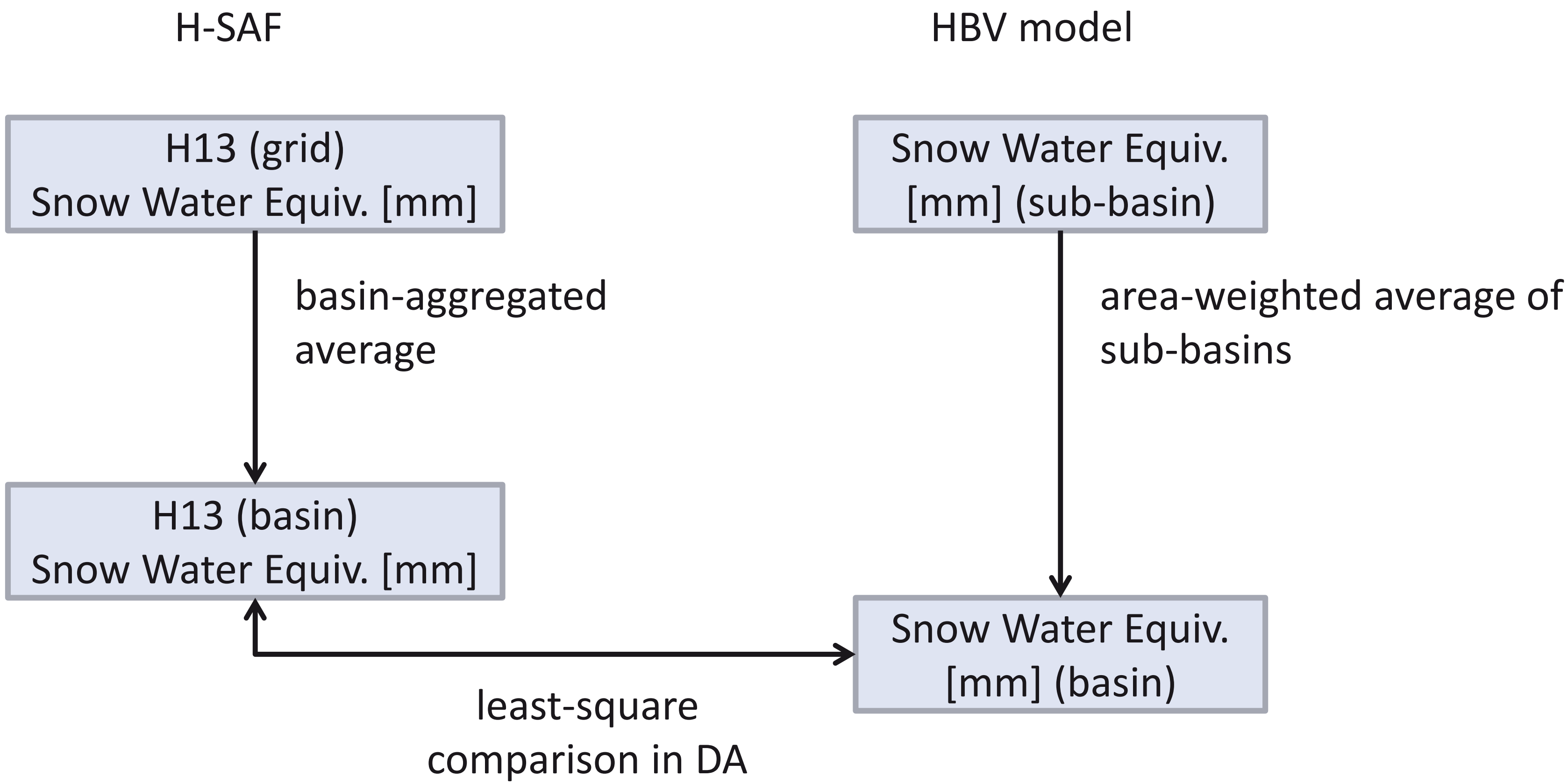

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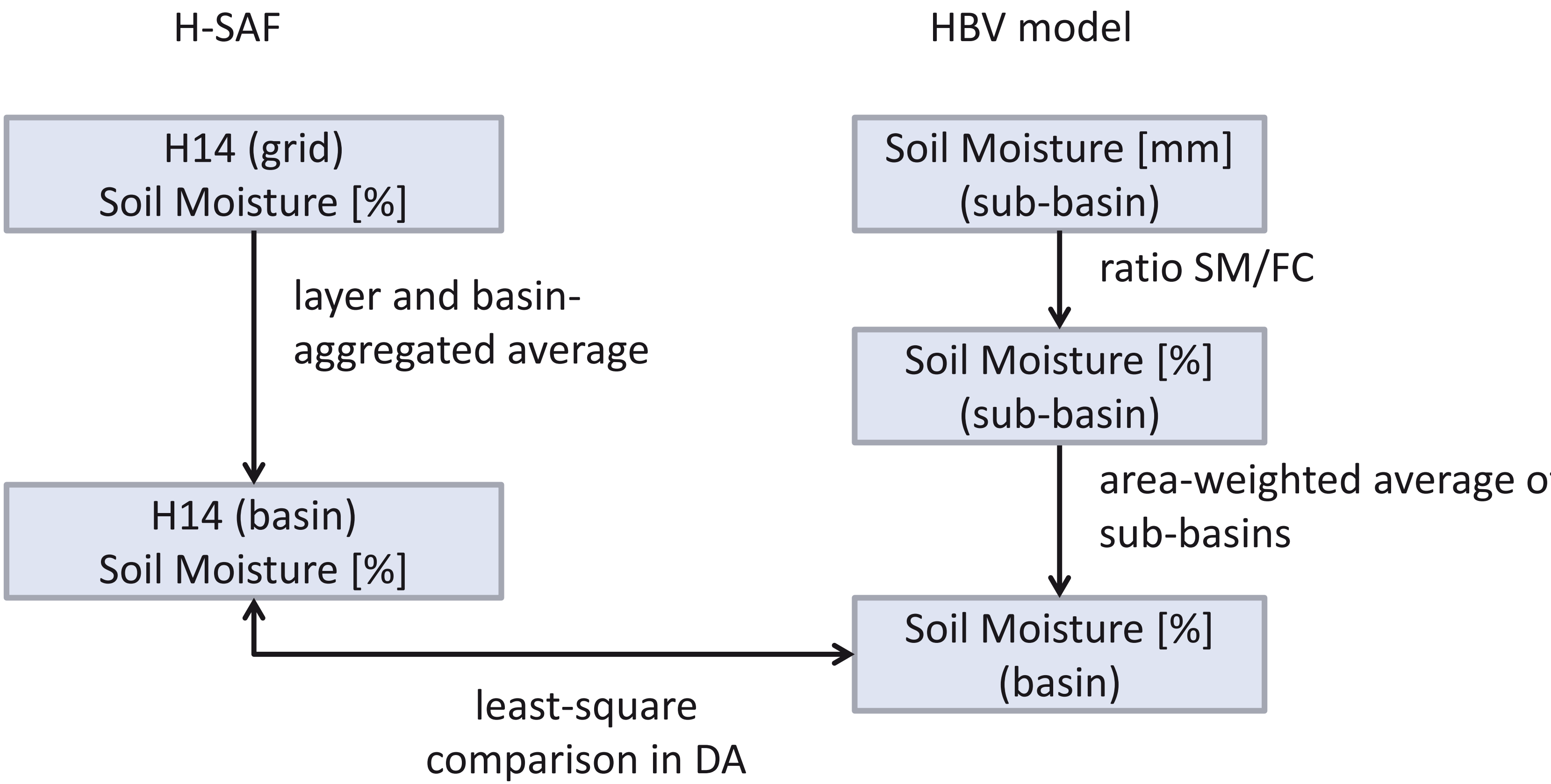
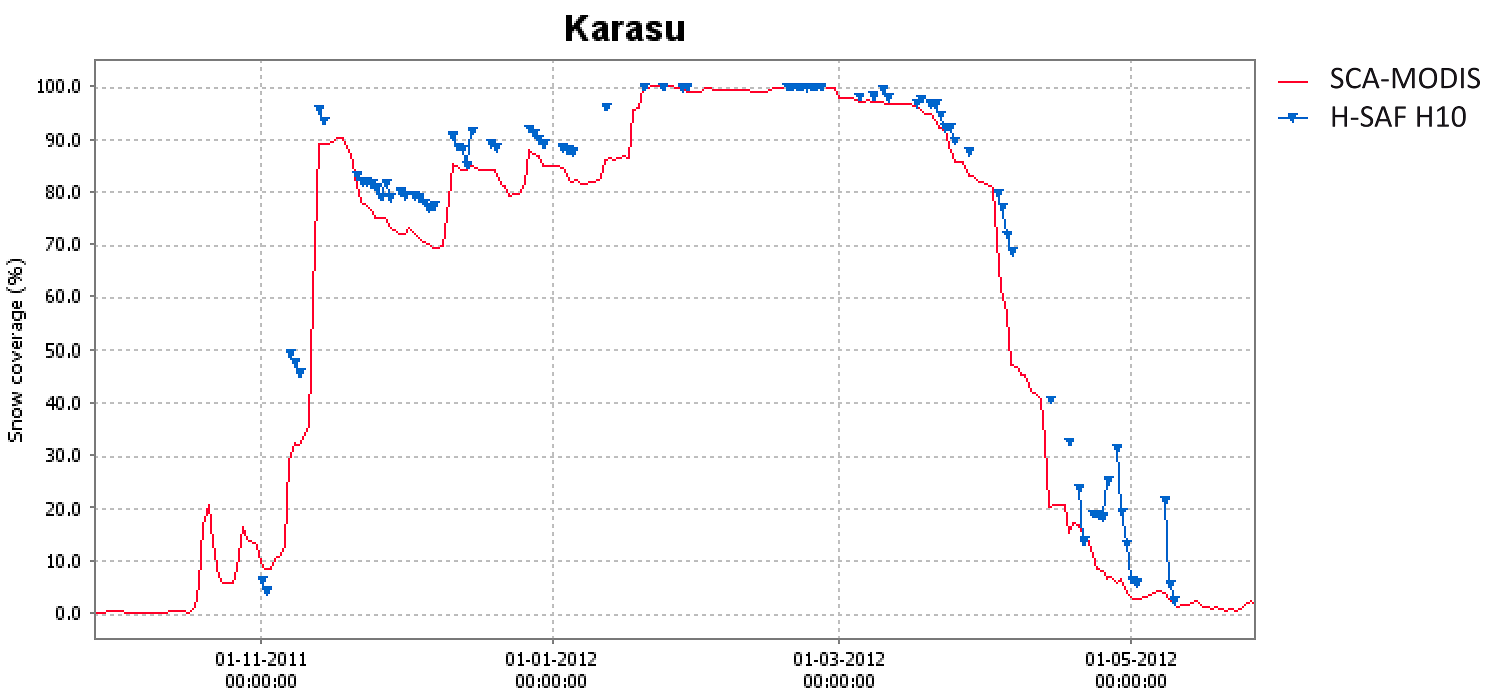


3rd Experiment – Practical Issues

Snow products for German test sites suffer from cloud coverage



3rd Experiment – Practical Issues

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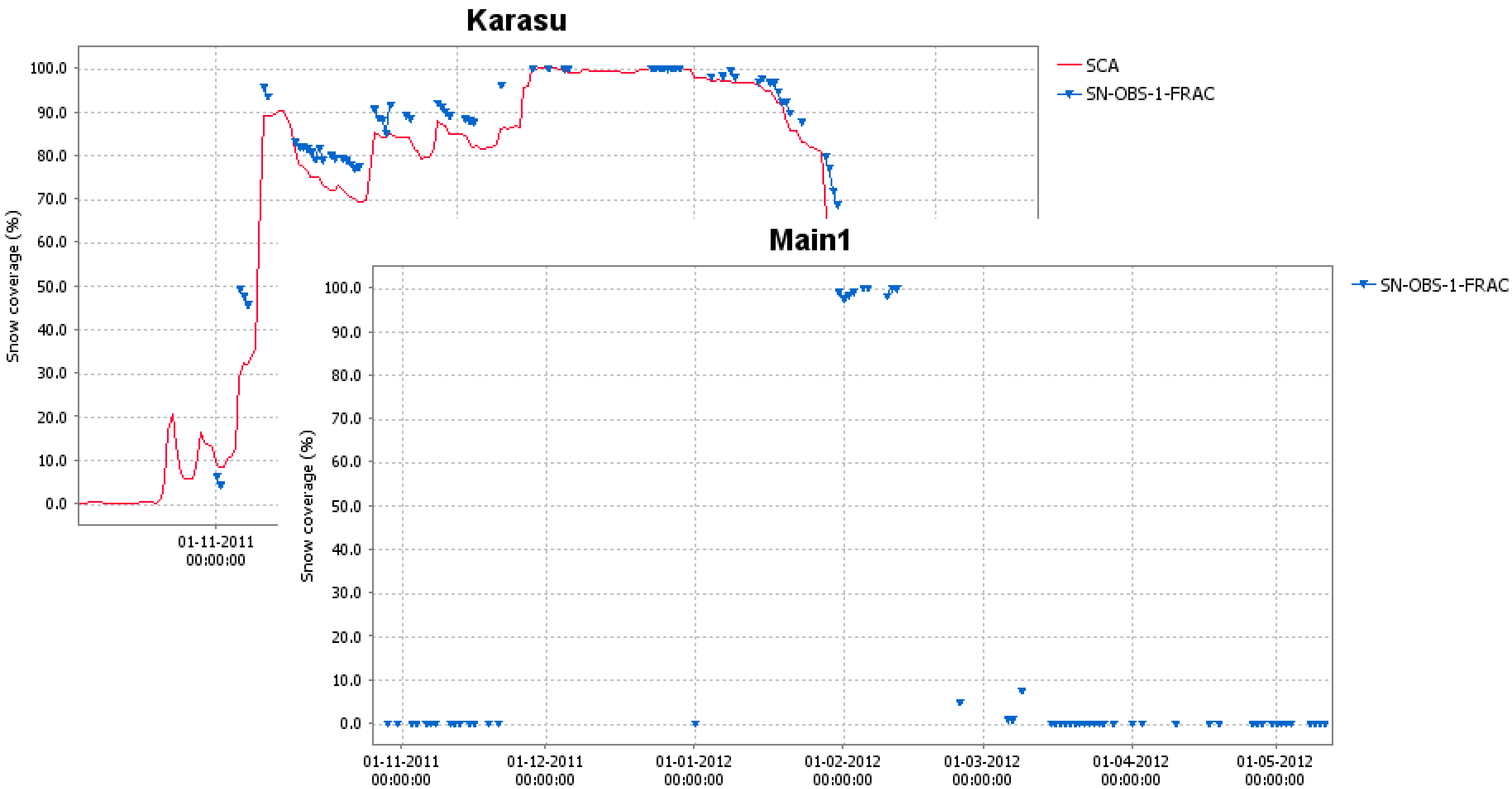
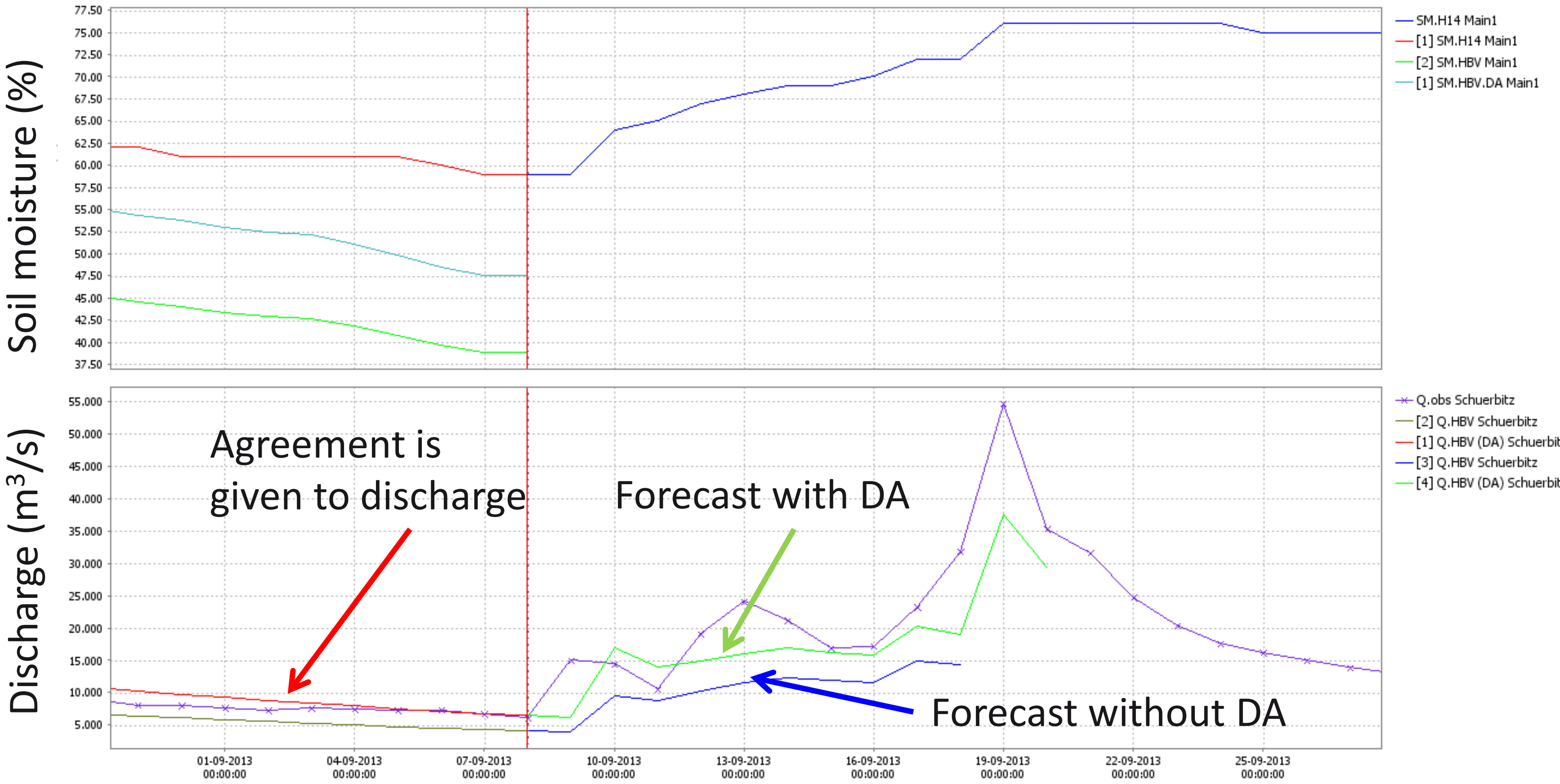


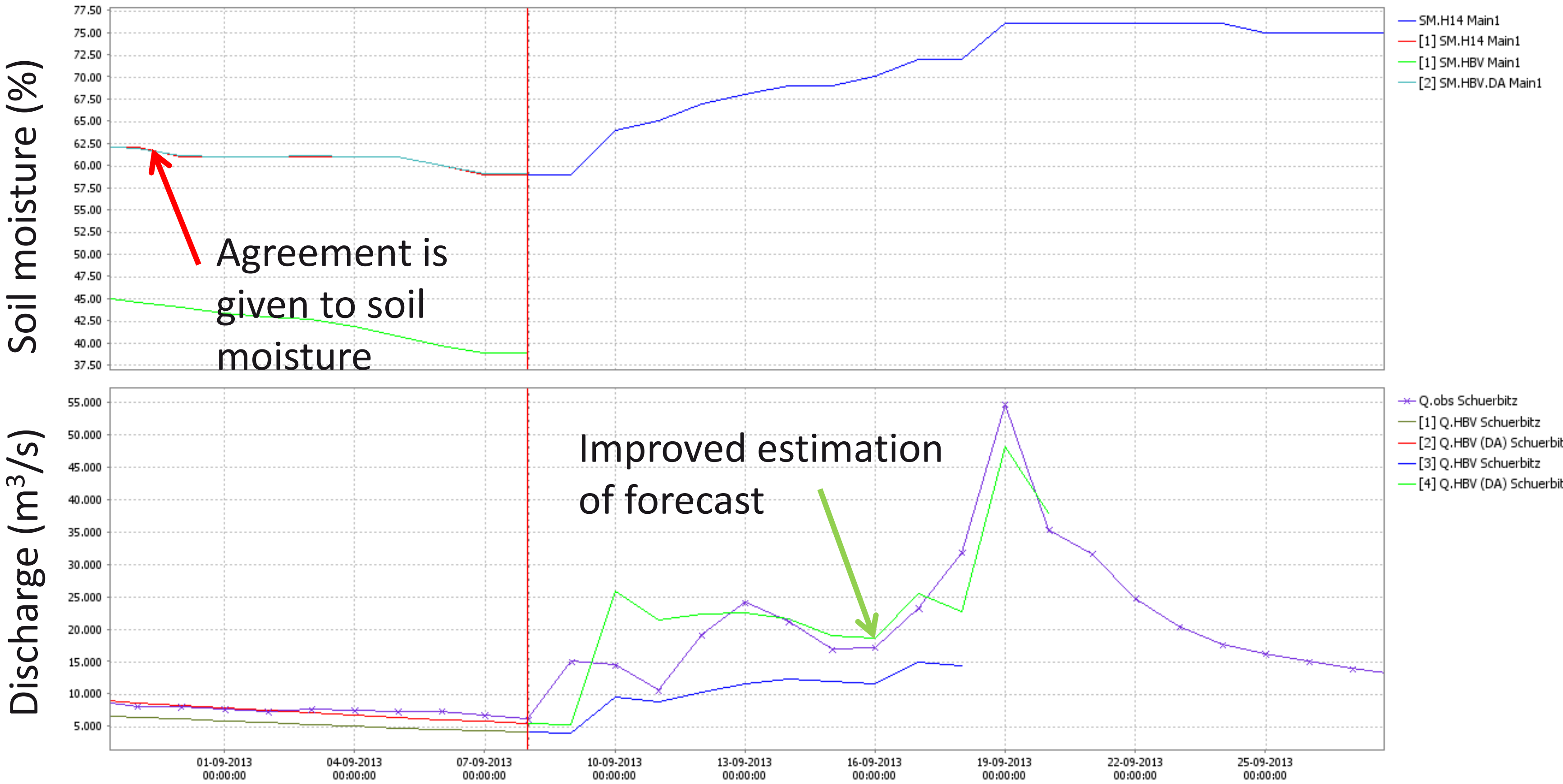
3rd Experiment

Data assimilation using a discharge agreement



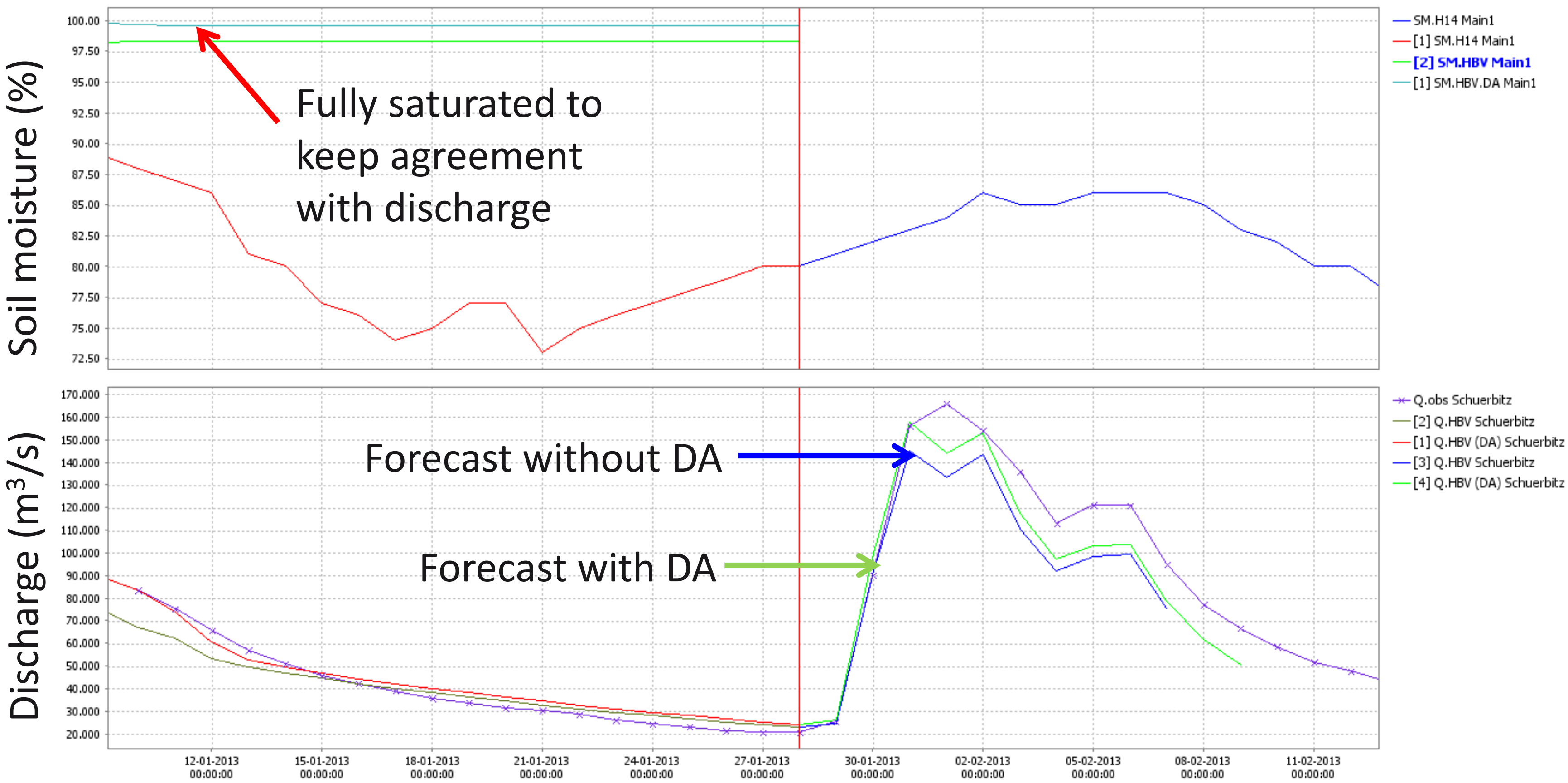
3rd Experiment

Data assimilation using soil moisture agreement



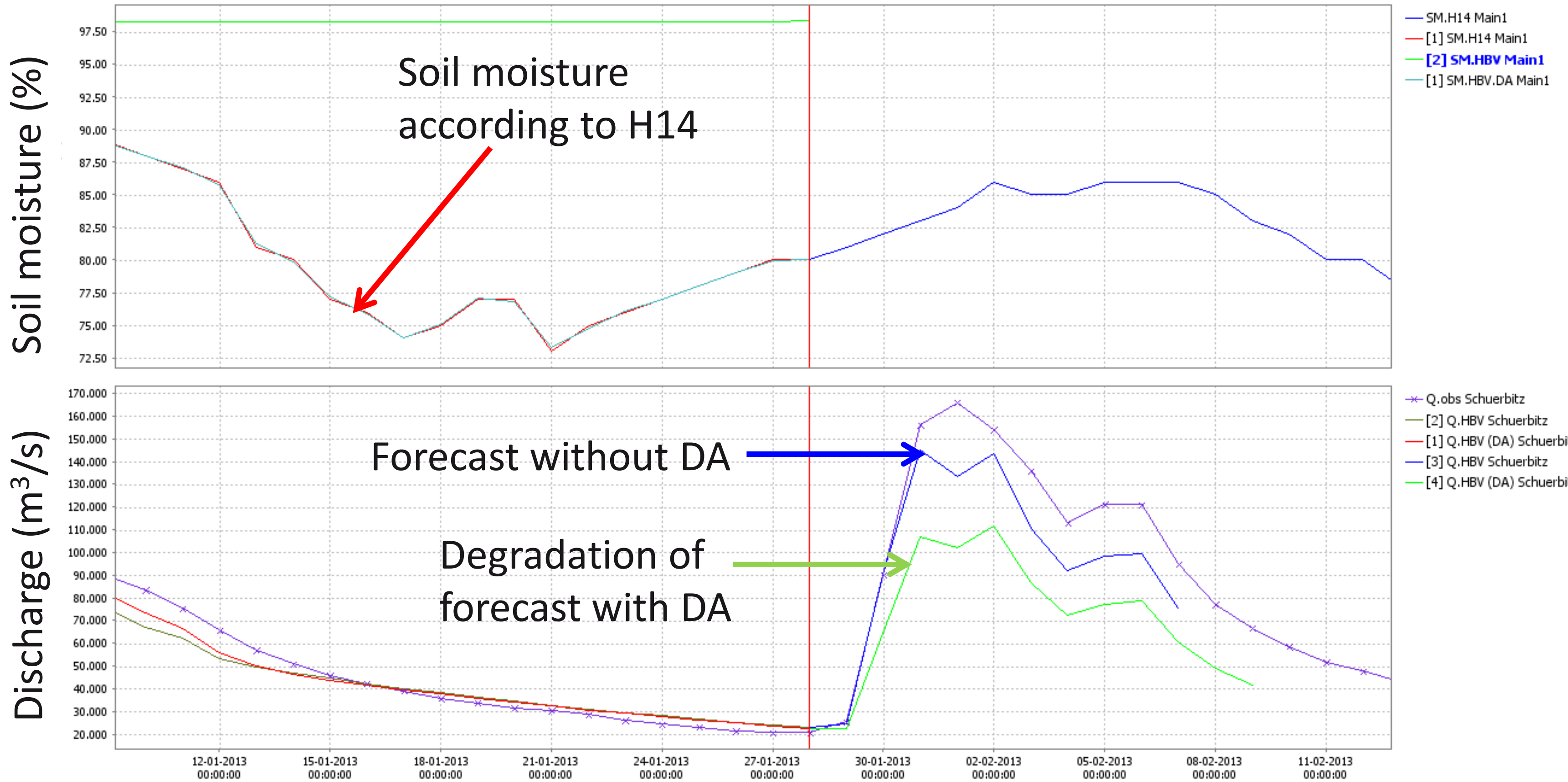
3rd experiment

Data assimilation using a discharge agreement



3rd Experiment

Data assimilation using a soil moisture agreement



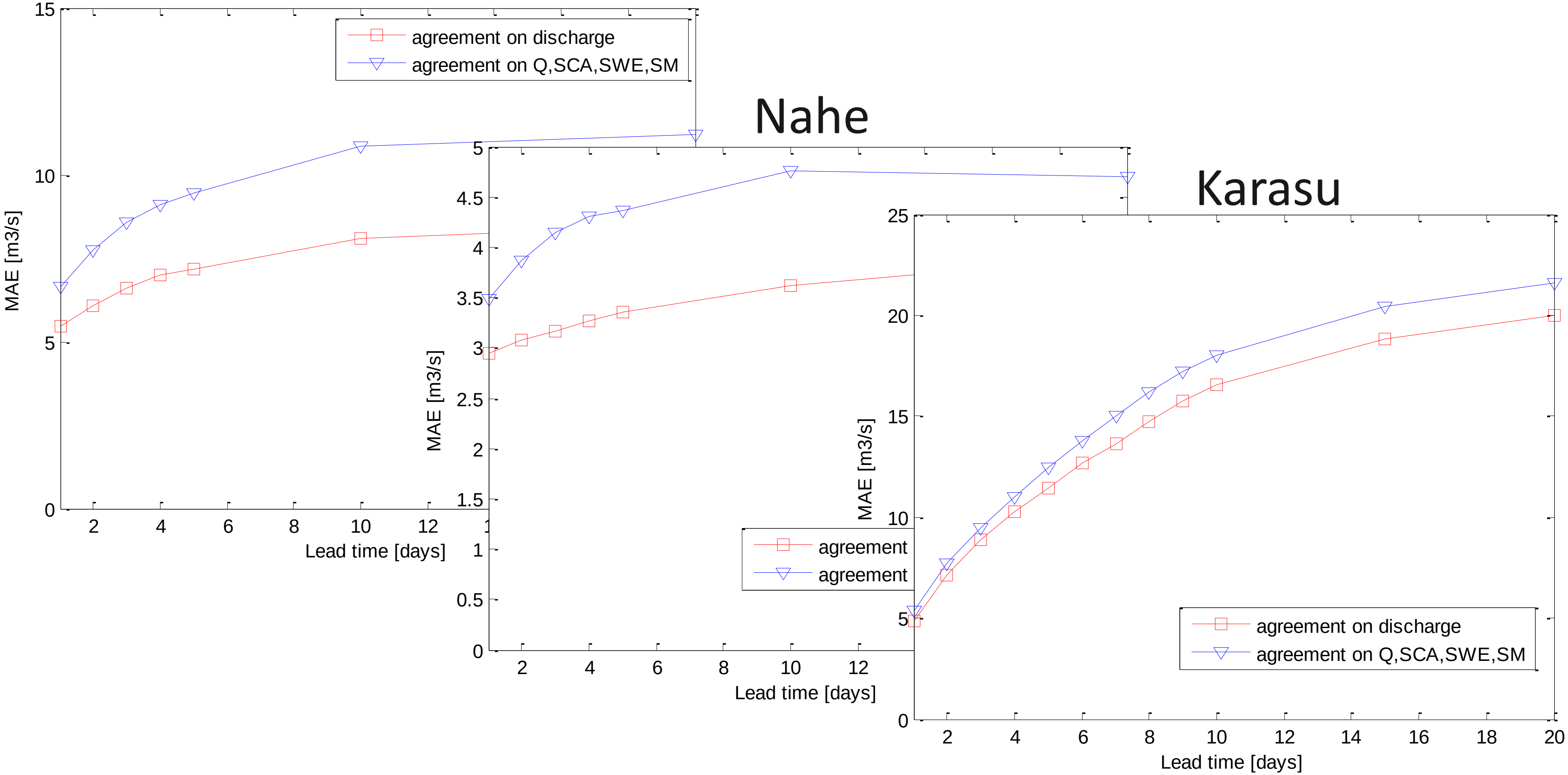
3rd Experiment

We run hindcasts experiments on each basin:

Main

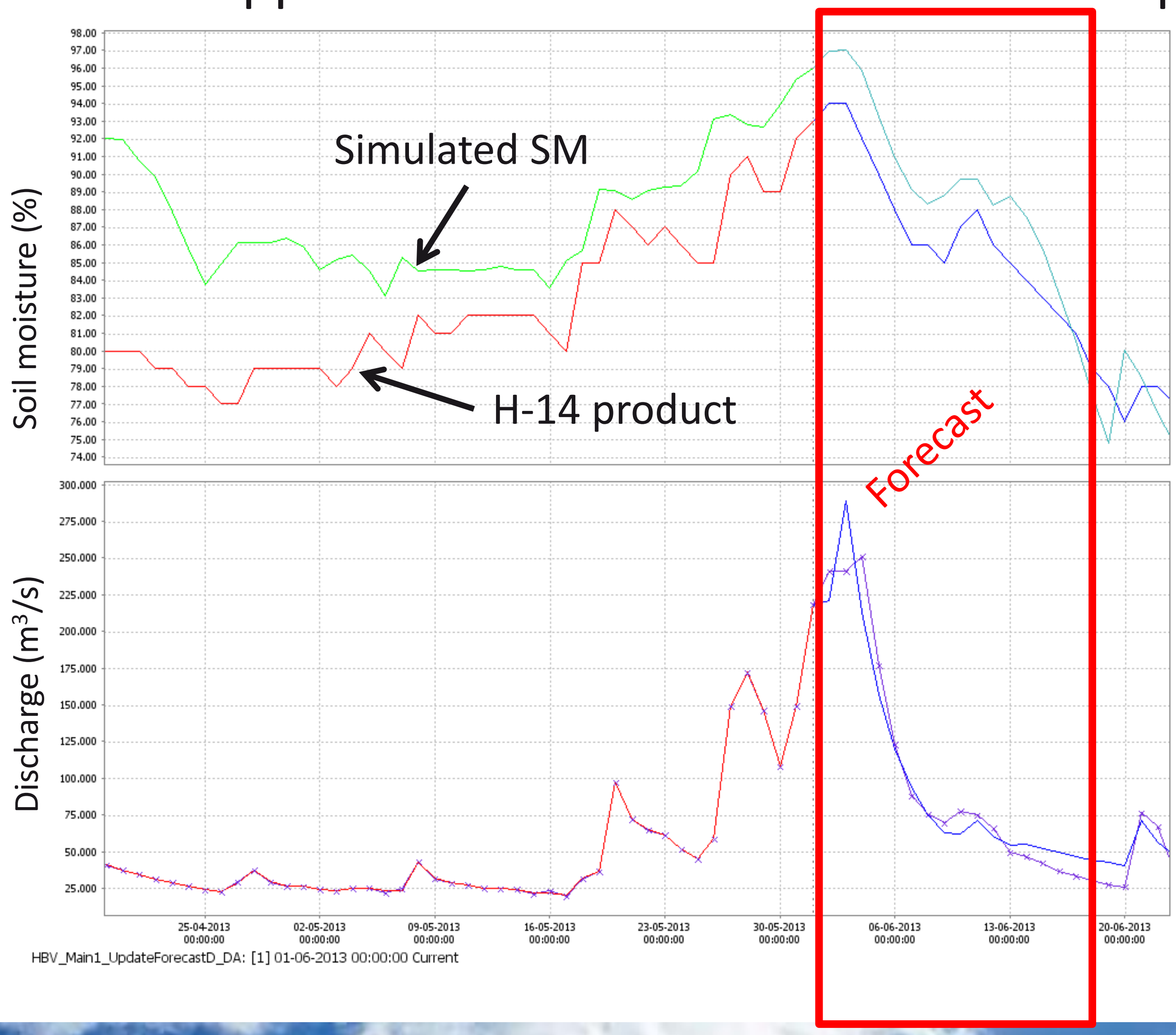
Nahe

Karasu



3rd Experiment – Other State Variables

What happens to the rest of the states? Example in Main…



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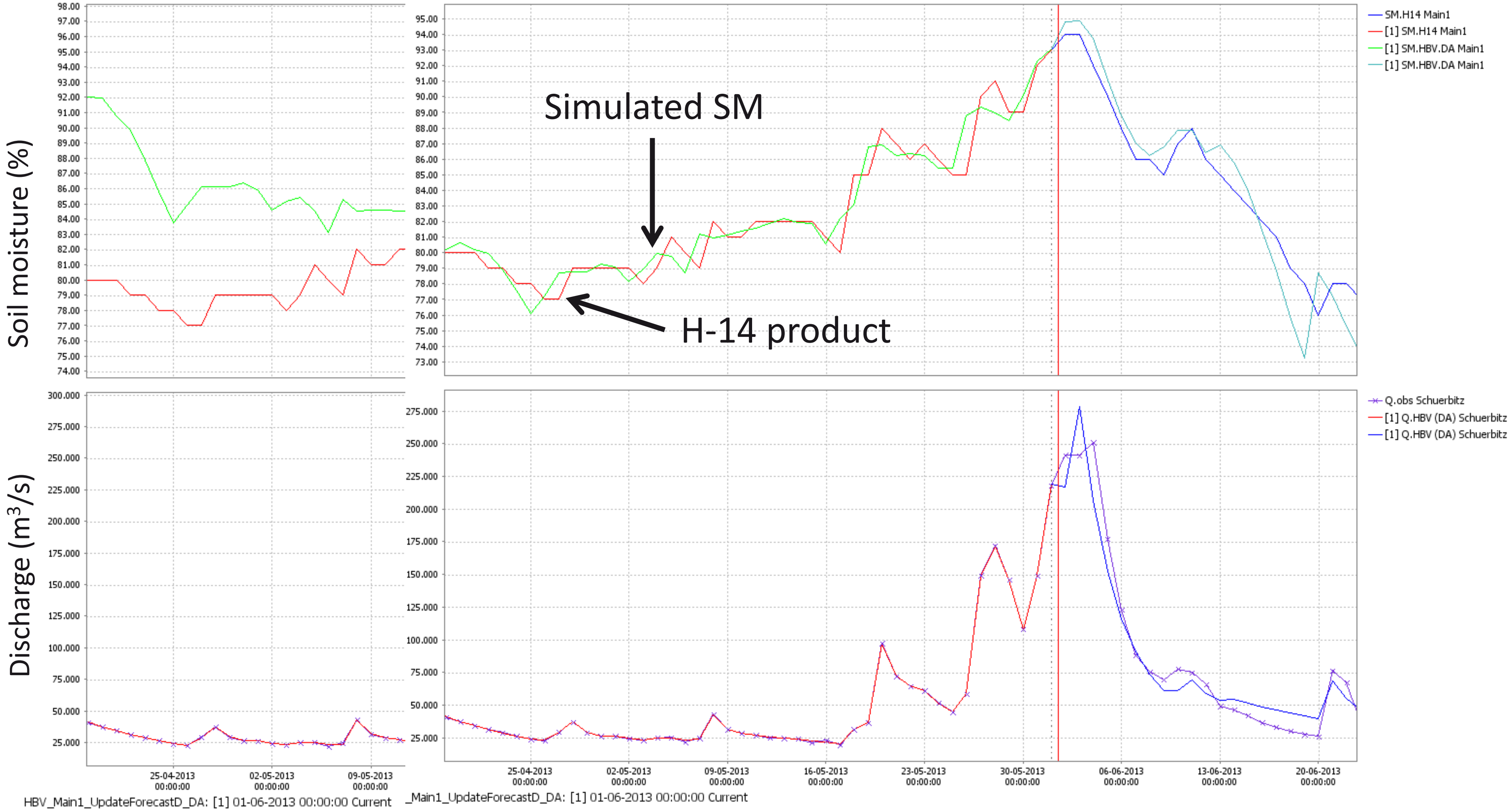
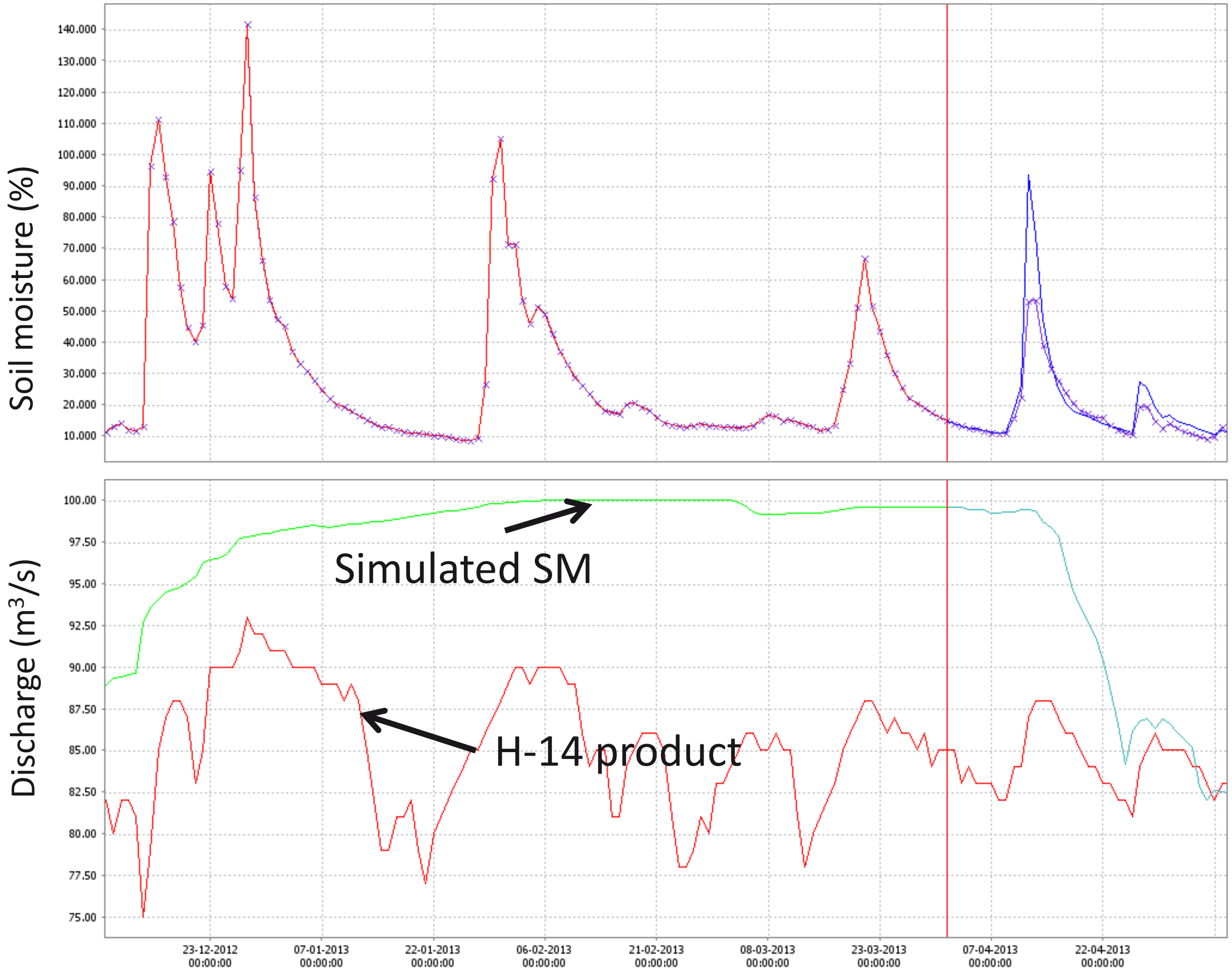


3rd Experiment – Other State Variables

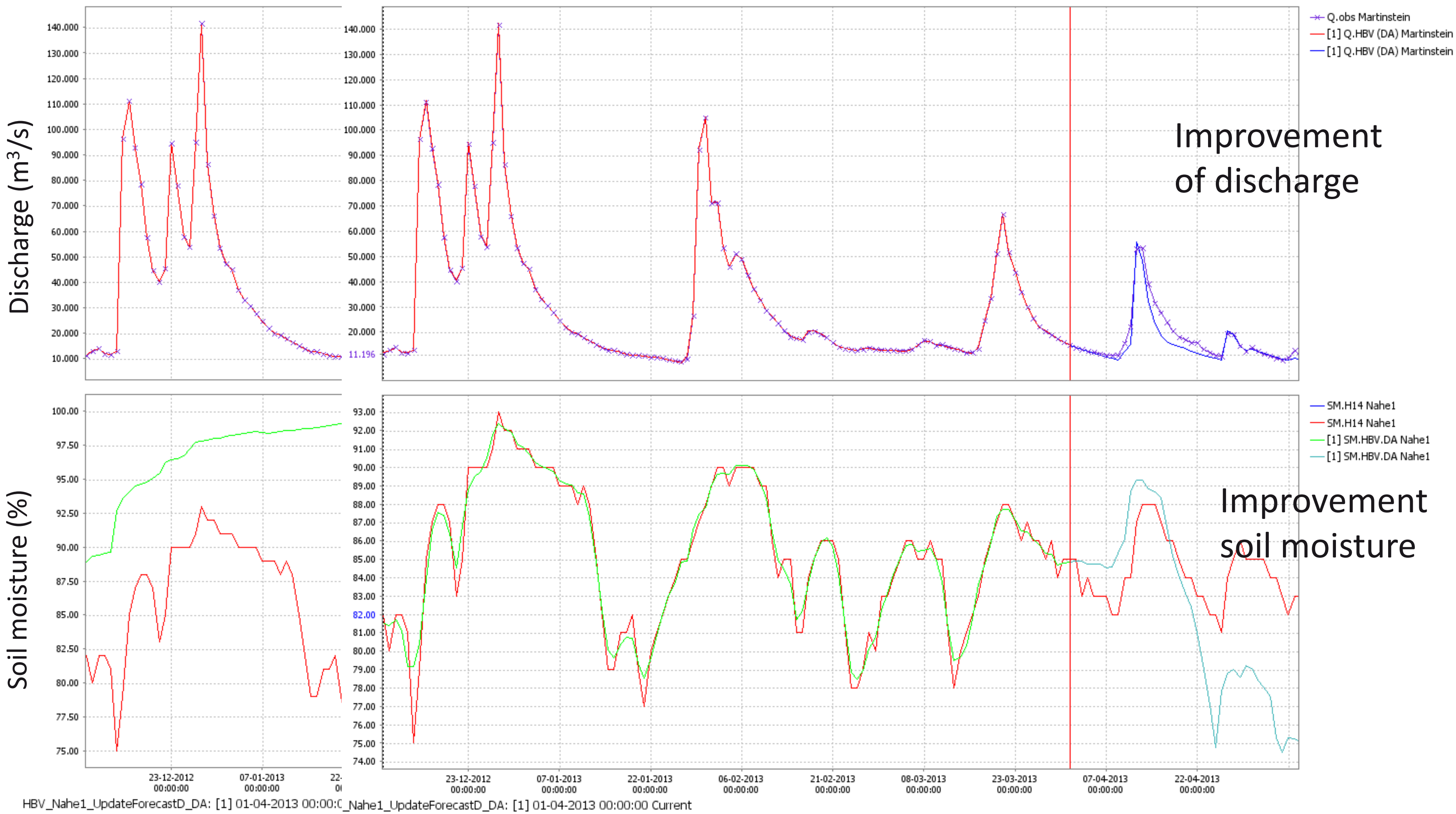
in Nahe basin…



HBV_Nahe1_UpdateForecastD_DA: [1] 01-04-2013 00:00:00 Current

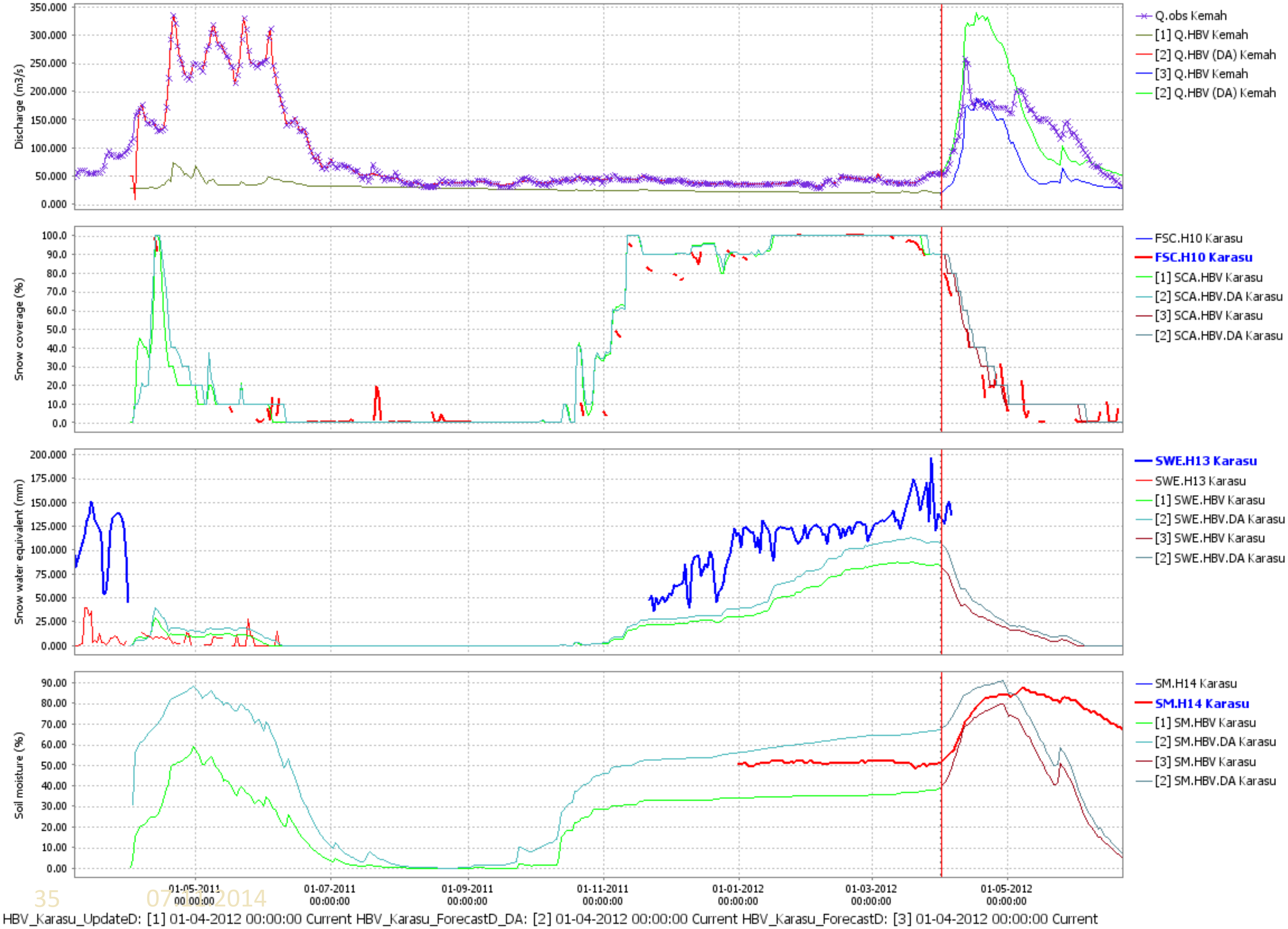
3rd Experiment – Other State Variables

in Nahe basin…



3rd Experiment – Other State Variables

in Karasu…



3rd Experiment – Other State Variables

in Karasu…

HBV_Karasu_UpdateD: [1] 01-04-2012 00:00:00 Current HBV_Karasu_ForecastD_DA: [2] 01-04-2012 00:00:00 Current HBV_Karasu_ForecastD: [3] 01-04-2012 00:00:00 Current

Conclusions

- Implementation of a generic and modular testbed for assimilating H-SAF products into rainfall-runoff model
- Data assimilation by MHE requires dedicated models (including adjoint models), but it is very efficient
- Application of methodolody using perfect forcing shows potential benefit of using the H-SAF products
- Performance metrics based on discharge do not show significant improvements when adding remote sensing data, more potential is in other model variables such as snow water equivalent and soil moisture
- H-SAF products have a greater impact in data-sparse environments; beneficial would be a global scale

Next Steps…

- Refinement and extension of the existing framework: review of the existing framework, consolidation of the configuration to make it more generic, integration of refined / extended H-SAF data, additional data sources, etc.
- Transition to a model pool
  - Semi-distributed and distributed model versions to study the impact of spatial resolution
  - Integration of additional model structures (Cosero extensions in HBV, etc.)
- Implementation of a test case in Poland
- Assessment of comparison of alternative DA approaches by integration of OpenDA, in particular different Kalman Filter techniques
- Open assimilation framework for H-SAF snow and soil moisture products for application in operational hydrological modeling systems

Thank you…

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