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

Rodolfo Alvarado Montero
Dirk Schwanenberg
Peter Krahe
Aynur Sensoy Sorman
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

- **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)
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:

\[
\begin{align*}
    \mathbf{x}^k &= f(\mathbf{x}^{k-1}, \mathbf{d}^k, \mathbf{u}^k) \\
    \mathbf{y}^k &= g(\mathbf{x}^k, \mathbf{d}^k, \mathbf{v}^k)
\end{align*}
\]

- States
- Output variable
- Disturbance/forcing vector
- 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:

\[
\begin{align*}
    \min_{\mathbf{u}, \mathbf{v}} \sum_{k=-N+1}^{0} & \left[ w_x \| \mathbf{x}^k - \mathbf{x}^k(u) \| + w_y \| \mathbf{y}^k - \mathbf{y}^k(u, v) \| + w_u \| \mathbf{u}^k \| + w_v \| \mathbf{v}^k \| \right] + w \| \mathbf{y} - \mathbf{y}^k \| \\
    \text{subject to} & \quad u_L \leq u^k \leq u_U \\
    & \quad v_L \leq v^k \leq v_U
\end{align*}
\]

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

Objective function

Observations

Hard constraints

Disturbance/forcing vector

Noise vectors
Variables and objective function terms in the MHE

<table>
<thead>
<tr>
<th>Variable</th>
<th>Objective Function Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation ($P$)</td>
<td>$w_P (\Delta P^k)^2$</td>
</tr>
<tr>
<td>Temperature ($T$)</td>
<td>$w_T (\Delta T^k)^2$</td>
</tr>
<tr>
<td>Snow Water Equivalent ($SWE = SP + WC$)</td>
<td>$w_{SWE} (\hat{s}^k_{SWE} - s^k_{SWE})^2$</td>
</tr>
<tr>
<td>Soil Moisture ($SM$)</td>
<td>$w_{SM} (\hat{s}^k_{SM} - s^k_{SM})^2 + w_{\Delta SM} (\Delta s^k_{SM})^2$</td>
</tr>
<tr>
<td>Upper Zone Storage ($UZ$)</td>
<td>$w_{\Delta UZ} (\Delta s^k_{UZ})^2$</td>
</tr>
<tr>
<td>Lower Zone Storage ($LZ$)</td>
<td>$w_{\Delta LZ} (\Delta s^k_{LZ})^2$</td>
</tr>
<tr>
<td>Snow Covered Area ($SCA$)</td>
<td>$w_Q (\hat{A}^k_{SCA} - A^k_{SCA})^2$</td>
</tr>
<tr>
<td>Discharge ($Q$)</td>
<td>$w_Q (\hat{Q}^k - Q^k)^2$</td>
</tr>
</tbody>
</table>
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 forests for Main1
- 5 elevation zones for Karasu

<table>
<thead>
<tr>
<th>Basin</th>
<th>Av. Flow</th>
<th>Calibration</th>
<th>Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Q [m³/s]</td>
<td>BIAS [m³/s]</td>
</tr>
<tr>
<td>Karasu</td>
<td>85.14</td>
<td>-1.49</td>
<td>33.22</td>
</tr>
<tr>
<td>Main1</td>
<td>31.05</td>
<td>1.37</td>
<td>11.26</td>
</tr>
<tr>
<td>Nahe1</td>
<td>15.65</td>
<td>-0.43</td>
<td>6.858</td>
</tr>
</tbody>
</table>

- 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
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

Assessment of maximum assimilation potential and model response

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

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

- Main1
- Nahe1
- Karasu
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)
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)
We run hindcasts during our validation period

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

H-SAF

H10 (grid)
Snow Coverage

basin-aggregated ratio of
snow / total visible cells if
sufficient cells are visible

H10 (basin)
Fractional SC [%]

HBV model

Snow Water
Equiv. (sub-basin)

transfer function

Fractional SC [%]
(sub-basin)

area-weighted average

Fractional SC [%]
(basin)

least-square
comparison in DA
**3rd Experiment – Procedures by Product**

**H-SAF**

- **H12 (grid)**
  - Fractional SC
  - basin-aggregated average if sufficient cells are visible

- **H12 (basin)**
  - Fractional SC [%]

**HBV model**

- **Snow Water Equiv. (sub-basin)**
  - transfer function

- **Fractional SC [%](sub-basin)**

- **Fractional SC [%](basin)**
  - area-weighted average

least-square comparison in DA
3rd Experiment – Procedures by Product

**H-SAF**

- H13 (grid)
  - Snow Water Equiv. [mm]

  basin-aggregated average

- H13 (basin)
  - Snow Water Equiv. [mm]

**HBV model**

- Snow Water Equiv. [mm] (sub-basin)

  area-weighted average of sub-basins

- Snow Water Equiv. [mm] (basin)

least-square comparison in DA
3rd Experiment – Procedures by Product

H-SAF

H14 (grid)
Soil Moisture [%]

layer and basin-aggregated average

H14 (basin)
Soil Moisture [%]

HBV model

Soil Moisture [mm]
(sub-basin)

d ratio SM/FC

Soil Moisture [%]
(sub-basin)

area-weighted average of sub-basins

Soil Moisture [%]
(basin)

least-square comparison in DA
Snow products for German test sites suffer from cloud coverage
3rd Experiment – Practical Issues

Snow products for German test sites suffer from cloud coverage
Data assimilation using a discharge agreement

Agreement is given to discharge

Forecast with DA

Forecast without DA
3rd Experiment

Data assimilation using soil moisture agreement

Agreement is given to soil moisture

Improved estimation of forecast
3rd experiment

Data assimilation using a discharge agreement

Fully saturated to keep agreement with discharge

Forecast without DA

Forecast with DA
3rd Experiment

Data assimilation using a soil moisture agreement

Soil moisture according to H14

Forecast without DA

Degradation of forecast with DA
3\textsuperscript{rd} Experiment

We run hindcasts experiments on each basin:

Main

Nahe

Karasu

- MAE [m$^3$/s]
- Lead time [days]
3rd Experiment – Other State Variables

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

![Graph showing soil moisture and discharge over time]

- Soil moisture (%)
- Discharge (m³/s)
- Simulated SM
- H-14 product
- Forecast
What happens to the rest of the states? Example in Main...

Simulated SM

H-14 product
3rd Experiment – Other State Variables

in Nahe basin...

Soil moisture (%)

Discharge (m³/s)

Simulated SM

H-14 product

HBV_Nahe1_updateForecast_Data [1] 01-04-2013 00:00:00 Current
3rd Experiment – Other State Variables

in Nahe basin...

Improvement of discharge

Improvement soil moisture
3rd Experiment – Other State Variables

in Karasu...
3rd Experiment – Other State Variables

in Karasu...
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 methodology 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...

Institute of Hydraulic Engineering and Water Resources Management
University of Duisburg-Essen
Faculty of Engineering
www.uni-due.de/wasserbau

Rodolfo Alvarado Montero
rodolfo.alvarado-montero@uni-due.de
Tel.: +49 201 183 4303