Snow Melt Runoff Simulation using Ensemble Kalman Filter assimilation of Distributed Snow Data

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Background

- Snow Melt Runoff predictions for Hydropower management in Sweden:
  - Hydrological model HBV
  - Snow depth and SWE data
    - Helicopter borne radar
    - Manual transects
  - Unclear if assimilation of this data improve predictions
Questions

• Model structure problem?
  - Day-degree or Energy Balance?
  - Lumped or Distributed?

• Data problem?
  - Non-representative?
  - Measurement errors? (e.g. Radar on wet snow)
  - Input data?

• Both?
  - Model structure and Data structure?
  - Data assimilation methods?
"HUVA" project

- Distributed measurement systems for improved snow melt runoff predictions – integration into hydrological models (KTH, LTU, KTH) – supported by ELFORSK/SVC

Objective:

- Investigate how the
  - model structure
    - (process representation, spatial distribution and temporal resolution)
  - Nature of snow data
    - (depth, mass, wetness, etc, distribution in space and time, measurement types)
- influence snow model predictions
Data assimilation

• What is the best estimate $x_a$ of the true state $x_{true}$ given an observation $y_0$ and a forecast state $x_{fo}$ at observation time?

$y_0 = y_{true} + \varepsilon$  observed quantity

$y_{fo} = h(x_{fo})$  observed quantity from model state

$x_{true}$ "true" state

$x_a$ analysis

$f(x_t, u_t, a) \rightarrow x_{fo}$ forecast

$x_t$ model

$\rightarrow t \rightarrow t+1 \rightarrow$ time
Data assimilation

- Best estimate by **Minimize cost function:**

\[
J = 0.5 \left( x - x_{fo} \right)^T B^{-1} \left( x - x_{fo} \right) + 0.5 \left( h[x] - y_o \right)^T R^{-1} \left( h[x] - y_o \right)
\]

\[
J \approx (\text{deviation from forecast})^2 + (\text{deviation from observation})^2
\]

- Model error
- Data error

B  error covariance matrix of model state x
R  error covariance matrix of observation y
EnKF ensemble Kalman filter

- Estimate covariance matrix from ensemble

\[ x_a = x_{fo} + K(y_o - h(x_{fo})) \]

\[ K = \frac{BH^T}{HBH^T + R} \]
Examples:

- Assimilation of distributed SWE data (at one time) into a distributed snowmodel
  - Improve the snow runoff volume?

- Assimilation of snow wetness data (time series) into a lumped model
  - Improve the snow melt timing?
Distributed snow hydrological model

Distribution

Meteorological forcing

Distributed (HRU) snow model

Model states

- Snow mass
- Snow depth
- Snow age
- Liquid water
- (Snow heat)

Process representation

Distribution of weather station data:

\[ P_{\text{local}} = (p_0 + p_1 \cdot \text{slope} + p_2 \cdot \text{curvature} + p_3 \cdot \text{windaspect}) \cdot P_{\text{station}} \]

\[ T_{\text{Local}} = T_{\text{station}} + L \cdot (\Delta \text{altitude}) \]

Day-degree model: \( M = c_T (T - T_f) + c_R R_s \)

(Energy balance model: \( M = (R_n - H - LE - c\delta T)/L_f \))

Distributed soil

Soil

Lumped soil

Unsaturated

Saturated

Energy balance model
Hydrological Responses Units (HRU)

- Modeling area has been classified into different classes depending on terrain properties.
- Combinations of Slope, Aspect, Curvature and Height have given a total of 124 different classes.

- Alternatively fully distributed on a rectangular grid
Study site: lake Korsvattnet, Jämtland

- Radar (GPR) snow data 2008-2009 (~20 km)
- Radar equipment carried by a snow mobile.
- Runoff to the lake

(84 km² watershed, 64°N13°E)
Automatic snow measurements

- Snow water equivalent SWE (snow pillow)
- Snow depth (ultrasonic)
- Snow wetness (impedance sensor)
- Snow temperature
Example 1: Distributed SWE data

# Assimilation of distributed data

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Model</th>
<th>Data Assimilated</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Lumped</td>
<td>No</td>
</tr>
<tr>
<td>2</td>
<td>Lumped</td>
<td>Average of distributed snow data(SWE)</td>
</tr>
<tr>
<td>3</td>
<td>Distributed (HRU)</td>
<td>No</td>
</tr>
<tr>
<td>4</td>
<td>Distributed (HRU)</td>
<td>Distributed data(SWE)</td>
</tr>
</tbody>
</table>
Without assimilation

Simulation nr 3.
Distributed model. No Data Assimilation

Snow depth and SWE simulated for the snow station

Runoff to the lake
With assimilation

Simulation nr 4.
Distributed model.

Observation
Modelled

Snow depth and SWE simulated for the snow station

Runoff to the lake
## Results (Korsvattnet)

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</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Lumped</td>
<td>No</td>
<td>-6.7</td>
<td>-5.8</td>
<td>0.64</td>
<td>0.91</td>
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<tr>
<td>2</td>
<td>Lumped</td>
<td>Average of dist snow data</td>
<td>-5.1</td>
<td>-3.4</td>
<td>0.61</td>
<td>0.92</td>
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<tr>
<td>3</td>
<td>Distributed (HRU)</td>
<td>No</td>
<td>-10.7</td>
<td>-8.6</td>
<td>0.67</td>
<td>0.87</td>
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<tr>
<td>4</td>
<td>Distributed (HRU)</td>
<td>Distributed data</td>
<td>8.43</td>
<td>-1.0</td>
<td>0.36</td>
<td>0.93</td>
</tr>
</tbody>
</table>
Example 2: Snow wetness data

Korsvattnet 2008-09

Snow and ice crust on cable in air

Early drop in SWE compared to snow pillow!

Overall good correspondance with snow pillow and manual
Simulated snow liquid water

![Graph showing liquid water volume fraction over days for different models: Reference model, Assimilation model, SPA measurement.](image-url)
Without assimilation

Assimilation of snow wetness data

Improved local snowmelt….but regional runoff deteriorated
(problem with snow depletion curve)
CONCLUSIONS AND OUTLOOK

• EnKF useful method for assimilation of snow data in hydrological models

• Acknowledge errors in both data and model

• Smooth automatic “update” of the models

• Data sets
  - Too few years to make general conclusions
  - 4 year with distributed data from project
  - ~15 years of old helicopter data further mined
Furthermore

- Implement snow assimilation routine into S-HYPE
- Evaluate operational snow depth measurements
Thank you!

Acknowledgement
This study was performed with support from the project “Distributed measurement systems for improved snow- and runoff forecasts – integration into hydrological models” supported by the "Swedish Hydropower Centre - SVC" [www.svc.nu](http://www.svc.nu). Björn Norell, Vattenregleringsföretagen AB Östersund, is acknowledged for support to the project.