SaskRB Modeling:
A multi-objective calibration approach Identification of hydrologic models using streamflow and Satellite water storage data
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CCRN Modelling Workshop (Modelling Change in Cold Regions)
Motivation
• Challenges in finding unique acceptable parameter estimates
• High uncertainties in flux and state variable estimations of hydrological modeling

Objective
• MESH Model parametrization with a multiobjective calibration approach that incorporate multiple metrics of streamflow and other independent variable observations
Case study area

- SaskRB Watershed area: 405,864 km$^2$
- Battle Watershed area: $\approx$30,000 km$^2$
- Vermilion Watershed area: $\approx$8,000 km$^2$
- Precipitation: up to 1500mm in the Rockies and 300-500mm in prairies
- DEM: 1:250,000 (Geobase Canada and USGS)
**GRACE Total Water Storage (TWS) anomaly**

- Gravity Recovery and Climate Experiment (GRACE), delivers monthly averages of the spherical harmonic coefficients describing the Earth’s gravity field, from which we infer time-variable changes in mass, averaged over arbitrary regions having length scales of few hundred kilometres to accuracies 1cm of equivalent water thickness.
- Monthly variation related to surface storage, soil moisture storage, groundwater changes, and Post Glacial Rebound
- We adopted GRACE TWS processed by Natural Resource Canada as in (Lambert et al., 2013) (Glacial Isostatic Adjustment (GIA) correction and filtering technique that that retain more signals)

**GRACE satellite (Photo credit: NASA)**

- **GRACE Monthly Storage Anomaly (mm) 01-2003**
- **GRACE BattleRB Total Water Storage Anomaly**

Swenson, 2012; Landerer and Swenson, 2012; Swenson and Wahr, 2006;
Soil and Landcover

Source: Soil landscape of Canada

Land cover data from the Canada Center for Remote Sensing (CCRS)
## Calibration parameters

<table>
<thead>
<tr>
<th>No</th>
<th>Parameters</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 &amp; 6</td>
<td>LAMX</td>
<td>Max LAI for grass and cropland resp.</td>
<td>3.5-4.0 4.0-6.0</td>
</tr>
<tr>
<td>2,5&amp;7</td>
<td>LNZ0</td>
<td>Nat. log roughness length for forest, grass and cropland resp.</td>
<td>0.0-0.405 -3.91- -2.5 -2.52- -1.38</td>
</tr>
<tr>
<td>1 &amp; 4</td>
<td>LAMNG</td>
<td>Min LAI forest and cropland resp.</td>
<td>0.5-1.6 3.0-3.5</td>
</tr>
<tr>
<td>8-10</td>
<td>SANDF</td>
<td>%tage sand content of layers forest 1-3</td>
<td>20-60%</td>
</tr>
<tr>
<td>11-13</td>
<td>CLAYF</td>
<td>%tage of clay content of layers forestland 1-3</td>
<td>25-40%</td>
</tr>
<tr>
<td>14-16</td>
<td>SANDG</td>
<td>%tage of sand content of grassland layers 1-3</td>
<td>20-65%</td>
</tr>
<tr>
<td>17-19</td>
<td>CLAYG</td>
<td>%tage of clay content of grassland layers 1-3</td>
<td>15-30%</td>
</tr>
<tr>
<td>20-22</td>
<td>SANDC</td>
<td>%tage of sand content of cropland layers 1-3</td>
<td>5-45%</td>
</tr>
<tr>
<td>23-25</td>
<td>CLAYC</td>
<td>%tage of clay content of cropland layers 1-3</td>
<td>27-40%</td>
</tr>
<tr>
<td>26</td>
<td>WFR21</td>
<td>River channel roughness factor</td>
<td>0.1-1.0</td>
</tr>
<tr>
<td>27,28&amp;29</td>
<td>BCR</td>
<td>Shape factor parameter for pareto distribution function: forest, grass and cropland</td>
<td>0.05-1.5</td>
</tr>
<tr>
<td>30,31&amp;32</td>
<td>CMAX</td>
<td>Maximum storage parameter [m] for pareto distribution function: forest, grass and cropland</td>
<td>0.1-2.0</td>
</tr>
</tbody>
</table>
Variogram Analysis of Response Surfaces (VARS)

Response Function:

\[ y = f(x) \]

where \( x = \{x_1, x_2, \ldots, x_n\} \)

Sample two points \( x^A \) and \( x^B \)

Distance: \( h = x^A - x^B \)

where \( h = \{h_1, h_2, \ldots, h_n\} \)

Variogram Function:

\[ \gamma(h) = \frac{1}{2} V(y(x + h) - y(x)) \]

Covariogram Function:

\[ C(h) = \frac{1}{2} \text{COV}(y(x + h), y(x)) \]

1) Direction
   Directional Variograms:
   \[ \gamma(h) \rightarrow \gamma(h_1), \ldots, \gamma(h_n) \]

2) Scale \( h = \{h_1, h_2, \ldots, h_n\} \)
VARS Sensitivity analysis

STREAMFLOW NSE

TWS ANOMALY NSE

Vegetation

Soil Parameters

Routing, PDMROF

Forest  Grass  Cropland

Forest  Grass  Cropland
Multiobjective optimization

\[
\begin{align*}
\text{minimize} & \quad [f_1(x), f_2(x), \ldots, f_M(x)] \\
\text{subject to} & \quad g_i(x) \leq 0 \quad i = 1, 2, \ldots, m \\
& \quad h_i(x) = 0, \quad i = 1, 2, \ldots, p \\
& \quad x = [x_1, x_2, \ldots, x_L]
\end{align*}
\]

\[f_1 = \text{Percentage Bias (Streamflow)}\]

\[PBIAS = \frac{\sum_{i=1}^{n} (Y_{i,\text{obs}} - Y_{i,\text{sim}}) \times 100}{\sum_{i=1}^{n} Y_{i,\text{obs}}}\]

\[f_3 = \text{Nash-Sutcliffe efficiency with logarithmic values (Streamflow)}\]

\[INSE = 1 - \frac{\sum_{i=1}^{n} (\log(Y_{i,\text{obs}}) - \log(Y_{i,\text{sim}}))^2}{\sum_{i=1}^{n} (\log(Y_{i,\text{obs}}) - \log(\bar{Y}_{\text{obs}}))^2}\]

\[f_2 = \text{Nash-Sutcliffe efficiency (Streamflow)}\]

\[NSE = 1 - \frac{\sum_{i=1}^{n} (Y_{i,\text{obs}} - Y_{i,\text{sim}})^2}{\sum_{i=1}^{n} (Y_{i,\text{obs}} - \bar{Y}_{\text{obs}})^2}\]

\[f_4 = \text{Nash-Sutcliffe efficiency (Storage anomaly)}\]

\[STNSE = 1 - \frac{\sum_{i=1}^{n} (ST_{i,\text{obs}} - ST_{i,\text{sim}})^2}{\sum_{i=1}^{n} (ST_{i,\text{obs}} - \bar{ST}_{\text{obs}})^2}\]
Multiobjective optimization

Multi-response MO

\[
\text{minimize } \quad [f_1(x), f_2(x), f_3(x)] \\
x \in \Theta \\
x = [x_1, x_2, \ldots, x_{32}]
\]

\[f_1 = \text{Percentage Bias (Streamflow)}\]

\[
PBIAS = \left[ \frac{\sum_{i=1}^{n} (Y_{i, \text{obs}} - Y_{i, \text{sim}})^*100}{\sum_{i=1}^{n} Y_{i, \text{obs}}} \right]
\]

\[f_3 = \text{Nash- Sutcliffe efficiency with logarithmic values (Streamflow)}\]

\[
INSE = 1 - \left[ \frac{\sum_{i=1}^{n} (\log(Y_{i, \text{obs}}) - \log(Y_{i, \text{sim}}))^2}{\sum_{i=1}^{n} (\log(Y_{i, \text{obs}}) - \log(Y_{i, \text{sim}}))^2} \right]
\]

Multivariate MO

\[
\text{minimize } \quad [f_1(x), f_2(x), f_3(x), f_4(x)] \\
x \in \Theta \\
x = [x_1, x_2, \ldots, x_{32}]
\]

\[f_2 = \text{Nash-Sutcliffe efficiency (Streamflow)}\]

\[
NSE = 1 - \left[ \frac{\sum_{i=1}^{n} (Y_{i, \text{obs}} - Y_{i, \text{sim}})^2}{\sum_{i=1}^{n} (Y_{i, \text{obs}} - \bar{Y}_{\text{obs}})^2} \right]
\]

\[f_4 = \text{Nash-Sutcliffe efficiency (Storage anomaly)}\]

\[
STNSE = 1 - \left[ \frac{\sum_{i=1}^{n} (ST_{i, \text{obs}} - ST_{i, \text{sim}})^2}{\sum_{i=1}^{n} (ST_{i, \text{obs}} - \bar{ST}_{\text{obs}})^2} \right]
\]
Borg Multiobjective optimization

- Five random seed runs
- 40,000 evaluation

\[ \epsilon_{BIAS}, \epsilon_{NSE}, \epsilon_{INSE}, \epsilon_{STNSE} = 0.001 \]
Multi-objective calibration using streamflow
Multi-objective calibration using both streamflow & TWS anomaly
Streamflow comparisons

**STREAMFLOW BASED**

05FE004 (Battle River near SK border Streamflow)

- Non-Dominated soil
- Obs

**COMBINED STREAMFLOW & TWS ANOMALY**

05FE004 (Battle River near SK border Streamflow)

- Non-Dominated soil
- Obs

Limitation

-1*NSE

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TWS anomaly comparisons

STREAMFLOW BASED

05FE004 (Battle River near SK border Storage Anomaly)

Storage (mm)

02-2004 07-2005 11-2006 04-2008 08-2009 12-2010

month-year

COMBINED STREAMFLOW & TWS ANOMALY

05FE004 (Battle River near SK border Storage Anomaly)

Storage (mm)

02-2004 07-2005 11-2006 04-2008 08-2009 12-2010

month-year

Limitation

-1*NSE

streamflow streamflow & storage

-0.7 -0.6 -0.5 -0.4 -0.3 -0.2 -0.1 0 0.1

-0.45 -0.5 -0.55 -0.6 -0.65 -0.7 -0.75 -0.8 -0.85 -0.9 -0.95 -1

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Parameter Uncertainties

**STREAMFLOW BASED**

- \( PBIAS \leq 5 \& \)
- \( NSE \geq 0.5 \& \)
- \( lNSE \geq 0.5 \)

**COMBINED STREAMFLOW & TWS ANOMALY BASED**

- \( PBIAS \leq 5 \& \)
- \( NSE \geq 0.5 \& \)
- \( lNSE \geq 0.5 \& \)
- \( STNSE \geq 0.5 \)
Validation on Vermilion River streamflow

STREAMFLOW BASED

05EE007 (Vermilion River near MARWAYNE)

COMBINED STREAMFLOW & TWS ANOMALY

05EE007 (Vermilion River near MARWAYNE)
Ongoing Testing on MODIS based ET, TWS and streamflow

Multivariate MO

\[
\begin{align*}
\text{minimize} \quad & \left[ f_1(x), f_2(x), f_3(x), f_4(x), f_5(x) \right] \\
x & \in \Theta \\
x & = [x_1, x_2, \ldots, x_{32}] 
\end{align*}
\]
Water means the WORLD to Us...

Global Institute for Water Security
www.usask.ca/water
Alternative calibration strategy

**GRACE BattleIRB Total Water Storage Anomaly**

\[
PF(i) = \begin{cases} 
0 & \text{Errbound}(i)_L \leq \text{Stosim}(i) \leq \text{Errbound}(i)_U \\
|\text{Stosim}(i) - \text{Errbound}(i)_L|^n & \text{Stosim}(i) < \text{Errbound}(i)_L \\
|\text{Stosim}(i) - \text{Errbound}(i)_U|^n & \text{Stosim}(i) > \text{Errbound}(i)_U 
\end{cases}
\]

**Objective fun**

\[
\text{Objective fun} = \sum_{i=n}^{nobs} PF(i)
\]
Multi-objective calibration using both streamflow & TWS anomaly