Terrestrial Hydrology in the Laurentian Great Lakes Watershed

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Analyze the **terrestrial water budget** in the **Great Lakes watersheds** using the **WRF-Hydro/NOAH-MP** modelling system.

Understanding the modalities of the terrestrial water budget is important because:

- Land surface processes affect lake levels and water quality
- Can help improve prediction capabilities of hydrological processes
Controls of Variability in the Laurentian Great Lakes Terrestrial Water Budget

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Terrestrial Water Budget

\[ \Delta SM + \Delta SWE + \Delta Aq + \Delta Can = Pt - ET - RO \]

\[ \Delta W \]

- **\( P_t \)**: Total precipitation
- **\( ET \)**: Land evapotranspiration
- **\( RO \)**: Surface + sub-surface runoff
- **\( \Delta W \)**: Change in terrestrial water storage

- **\( SM \)**: Soil moisture in the top 2-meter soil layer
- **\( SWE \)**: Snowpack water equivalent
- **\( Aq \)**: Aquifer recharge
- **\( Can \)**: Canopy interception
National Water Model (NWM) configuration for physics parameterizations

Atmospheric forcing: North American Mesoscale (NAM) 12-km, 6-hourly analysis

Oct 2016 – Sep 2020 (4 hydrological years)

10-year treadmill spin-up
Study objectives

1. Identify the **dominant quantities** contributing to the **variability in the land surface hydrology** at different timescales

2. Study the **relationships between the budget quantities** and the relative contributions of change in each variable from other components
PCA is a multivariate dimensionality reduction method:

- Reduces the number of observed variables to components which account for the most variability in the system
- Can help identify variables more important to characterize the hydrological regime

We conducted PCA over two temporal scales for each basin:

(1) Spatially averaged, daily time series → to explain the sub-seasonal variation

(2) Spatially averaged, monthly timeseries → to explain seasonal variation
In summer (Jun – Sep), the first PC accounts for nearly all the variance (>97%) in the five basins.

In the colder months (Nov – Mar), PC2 also explains a large percentage of the variability in the water budget (~ 40% for some months)

- For Superior, which is located at higher latitudes, PC2 contributes more to Feb – May (25 – 42%) variability
- In Erie, PC2 effect is larger in Dec – Feb (27 – 40%)
## PCA results: Sub-seasonal timescale

In summer and autumn (May – Oct), PC1 is highly correlated with only two variables in all basins:

- Precipitation (correlation coefficient varying from 0.72 – 0.76, depending on basin)
- Change in soil moisture (correlation of 0.63 – 0.69)

In the colder months (Nov – Apr), there are differences amongst the basins and the role of ground snow accumulation emerges.

PC2 is also almost entirely correlated with these three variables.

### Table 1: Correlation of PC1 and PC2 with Variables

<table>
<thead>
<tr>
<th>Season</th>
<th>PC1</th>
<th>PC2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation</td>
<td>Superior Erie</td>
<td>Superior Erie</td>
</tr>
<tr>
<td>ET</td>
<td>Superior Erie</td>
<td>Superior Erie</td>
</tr>
<tr>
<td>RO</td>
<td>Superior Erie</td>
<td>Superior Erie</td>
</tr>
<tr>
<td>ΔSM</td>
<td>Superior Erie</td>
<td>Superior Erie</td>
</tr>
<tr>
<td>ΔSWE</td>
<td>Superior Erie</td>
<td>Superior Erie</td>
</tr>
</tbody>
</table>

### Correlation Table

<table>
<thead>
<tr>
<th>Correlation</th>
<th>1.0 – 1</th>
<th>0.8 – 0.6</th>
<th>0.6 – 0.4</th>
<th>0.4 – 0.2</th>
<th>0.2 – 0.0</th>
<th>0</th>
<th>0.0 – 0.2</th>
<th>0.2 – 0.4</th>
<th>0.4 – 0.6</th>
<th>0.6 – 0.8</th>
<th>0.8 – 1</th>
</tr>
</thead>
</table>

Hatching for months where variance explained is <10%
Key findings

1) **Precipitation** is a year-round important variable in the budget for all basins, not just in terms of magnitude, but also in explaining the variability in the system.

2) **Soil moisture** is a particularly dominant variable for the entire domain in the summer months, and for the southern basins year-round.

3) **Snowpack** is important for the colder season, especially for the northern basins, and less so for Erie.

4) **ET and runoff**, which have relatively large overall magnitudes, and are important quantities in any terrestrial water budget, have no contribution in explaining the variability in the budget.
More components (PCs 1 – 4) are needed to explain the maximum variance

Importance of other processes emerges along with greater differences amongst the basins

- In Superior, PC1 is strongly correlated with ΔSWE, PC2 with precipitation, and PC3 primarily with ΔSM.
- In Erie, $P_t – ET – RO$ quantities dominate the budget variability
PCA results: Seasonal timescale

**Northern region:** snowpack and precipitation are the drivers of variability

**Middle domain:** role of evapotranspiration and soil moisture becomes evident

**Southern region:** precipitation-evapotranspiration-runoff nexus is the dominant source of variability
1. Identify the **dominant quantities** contributing to the **variability in the land surface hydrology** at different timescales

2. Study the **relationships between the budget quantities** and the relative contributions of change in each variable from other components
Partial Least Squares Regression (PLSR)

PLSR is another multivariate statistical approach which projects data to a new component space:

➢ **Key distinction from PCA:**
  ➢ It establishes a relationship between a dependent variable (response variable) and a set of independent variables (explanatory variables)
  ➢ VIP score (variable influence on projection) measures the importance of each explanatory variable for the response variable.

We use the PLSR approach to establish the most important predictor variables that drive change in each budget quantity at seasonal timescales.
PLSR results: Relationship among the terrestrial budget quantities

ΔAq changes are driven by ΔSWE in Superior, and ET and ΔSM in the other watersheds.

A VIP score >1 is considered important for the projection.
PLSR results: Relationship among the terrestrial budget quantities

Runoff dependence is primarily on ΔSWE for Superior, Michigan, and Huron. In the southern basins, precipitation is the main driver of variability in runoff.

Bidirectionality in some links, for example, the ΔSM – ET dependence in Erie.

Change in one quantity can be a predictor of fluctuations in another – these “predictors” of each quantity vary for the five watersheds.
The Great Lakes domain is not a hydrologically uniform regime, and the basins have differences in the dominant regulators of water budget.

Dominant quantities characterizing the subregional terrestrial hydrology vary for daily, monthly, and annual timescales.

Climate change impact studies on regional hydrology need to account for basin-scale differences in the terrestrial hydroclimatic dynamics.

Future work

- Provides baseline to assess modifications in the budget due to changes in the atmospheric forcing
  - **Next step:** Quantify the effects of changes in atmospheric forcing e.g., temperature (warming/cooling) and precipitation (magnitude and phase) on the terrestrial water budget
Questions

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Surface runoff schemes

RUNOFF_OPTION = 1
!
1 -> TOPMODEL with groundwater (Niu et al. 2007 JGR);
2 -> TOPMODEL with an equilibrium water table (Niu et al. 2005 JGR);
**3 -> original surface and subsurface runoff (free drainage);
4 -> BATS surface and subsurface runoff (free drainage)
Surface runoff schemes

- Magnitude differences between the two schemes are small
- TOPMODEL has slightly higher magnitudes - especially in regions where soils are Loam/Silty Loam (i.e., southern regions of the domain)
## Output evaluation and validation

<table>
<thead>
<tr>
<th>Variable</th>
<th>In-situ</th>
<th>Observation-based</th>
<th>Satellite-derived</th>
<th>Reanalysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation</td>
<td></td>
<td>CRUv4.05</td>
<td></td>
<td>ERA5, MERRA2</td>
</tr>
<tr>
<td>Evapotranspiration</td>
<td></td>
<td></td>
<td>GLEAM v3.5b</td>
<td>ERA5, MERRA2</td>
</tr>
<tr>
<td>Runoff</td>
<td>USGS gauges</td>
<td></td>
<td></td>
<td>ERA5, MERRA2</td>
</tr>
<tr>
<td>Soil moisture</td>
<td></td>
<td></td>
<td>SMAP-HB</td>
<td>ERA5, MERRA2</td>
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<tr>
<td>SWE</td>
<td></td>
<td></td>
<td></td>
<td>ERA5, MERRA2</td>
</tr>
<tr>
<td>Canopy interception</td>
<td></td>
<td></td>
<td></td>
<td>ERA5</td>
</tr>
</tbody>
</table>
Runoff validation (USGS gauges)
Output evaluation (Reanalysis and gridded products)

Lake Erie basin

ET (mm d\(^{-1}\))

RO (mm d\(^{-1}\))

SWE (mm w.e.)

NOAH-MP    ERA5-L    MERRA-2 L

GLEAM v3.5b
ET has a distinct seasonal cycle with the maxima in July for all basins

- All other variables have inter- and intra-annual and basin-wide differences

- Runoff generally peaks in spring (March – May): southern regions peak earlier, and Superior runoff maximum is in May

- The absolute magnitude of ΔSWE for Erie is small and highest for Superior

- Change in canopy interception is orders of magnitude smaller and can be ignored
For the annual budget magnitudes:

- The water budget is controlled by the Pt–ET–RO nexus
- Change in terrestrial water storage ($\Delta W$) is negligible
- But high standard deviation in the snowpack ($\Delta SWE$) and soil moisture ($\Delta SM$) → importance of terrestrial water storage at sub-annual timescales