Integration of remote sensing data into a watershed-scale wetland modeling for an improved model prediction

Sangchul Lee
Ph.D. candidate at the Univ. of MD, College Park
Wetland hydrology

- Wetland ecosystem functions
  - Mitigating flood damage
  - Improving water quality by reducing pollution loads
  - Serving as natural habitats to support biodiversity

- This ecosystem functioning highly relies on the hydrological characteristics of wetlands (e.g., hydro-period).
  - Hydro-period: duration and frequency of inundation and soil saturation at a specified depth
A watershed model

- Soil and Water Assessment Tool (SWAT)
  - One of watershed models to predict the cumulative impacts of multiple wetlands in the watershed.

- Previous application
  - Simulating wetland loss and restoration scenarios (Yang et al., 2010; Records et al., 2014)
  - Identifying the optimal locations for wetland restoration (Babbar-Sebens et al., 2013)
  - Investigating wetland effects on streamflow during dry and wet periods (Wu and Johnston, 2008)
Limits in a wetland module of SWAT

Wetland representation:
- Watershed boundary
- Sub-watershed boundary
- Stream
- Wetland
- Aggregated wetland

Wetlands within a sub-watershed are aggregated into one wetland.

Physical processes:
- SR: Surface runoff, G: Ground water, SE: Seepage, E: Evaporation, P: Precipitation

Unidirectional flow from wetlands to streams:
- Outflow to main channel
- Inflow
Necessity of spatially-distributed inundation information #1

- Limited in wetland parameterization
  - Surface area and volume of a wetland at normal and maximum water levels
  - Uniform characteristics for all wetlands

### Parameterization

- Watershed boundary
- Sub-watershed boundary
- Stream
- Maximum wetland area
- Normal wetland area
- Maximum wetland depth (m)
- Normal wetland depth (m)

### Actual condition

- Constant wetland geomorphic characteristics

### General approach
Necessity of spatially-distributed inundation information #2

- Limited in assessing the wetland module performance
  - Observed streamflow - an aggregate response of the watershed
  - The wetland module has an insignificant impact on model performance - if SWAT is well calibrated without the wetland module, the model performance is evaluated as “satisfactory” regardless of the wetland module.
- Model uncertainty in wetland parameters
  - “Equifinality”: multiple parameter sets produce similar or acceptable model outputs
Remote sensing data #1

- **Inundation maps** (Huang et al., 2014)
  - Inundation percentage at 30-meter pixel based on the statistical relationship between Light Detection and Ranging (LiDAR) and time series Landsat records.

![Relationship between Landsat and Validation Data Before and After Correction](image_url)

Mean SIP values of the initial 2007 RT prediction were lower than the mean reference SIP within 2% bins.

Biases were corrected by fitting a 2nd order polynomial function between mean reference values and mean predictions.

SIP: Sub-pixel Inundation Percentage
Remote sensing data #2

- Inundation maps under different climate conditions
  (Huang et al., 2014)

- Average condition (2005)
- Average condition (2007)
- Dry condition (2009)
- Wet condition (2010)

SIP: Sub-pixel Inundation Percentage
Objective

- To integrate remote sensing data into SWAT for an improved prediction on inundated areas within riparian wetlands

- To assess the capacity of wetlands to regulate downstream water
Study Area

- Headwater forested wetlands in the Choptank River Watershed
  - Coastal Plain of the Chesapeake Bay Watershed
  - Wetlands are mostly depressional.
  - NWI distribution: 34.5 km² (15.5% of the watershed)
  - Land use: Agriculture (51.3%) and forest (38.4%)
Wetland modeling

- Riparian Wetlands (RWs)
  - Wetland polygons intersect with the stream map
  - Simulated using Riparian wetland module, a SWAT extension - water exchange between a stream and RW at the sub-water scale (Liu et al., 2008)

- Non-Riparian Wetlands (NRWs)
  - Wetland polygons away from the stream map
  - Simulated using a wetland module of SWAT

- Aggregated RW and NRW at the sub-watershed scale

<table>
<thead>
<tr>
<th>Type</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>RW</td>
<td>13.4 km²</td>
</tr>
<tr>
<td>NRW</td>
<td>21.1 km²</td>
</tr>
</tbody>
</table>
Wetland parameterization #1

- Using NWI and inundation map, spatially-varying wetland geomorphic parameters were estimated.
- Maximum wetland area and depth (NWI map)
  - Aggregated surface area of wetlands within a sub-watershed
  - Aggregated volume of wetlands derived from the method of Lane and D’Amico (2010)
  - Depth = Volume / Surface Area (assuming the geometry of a wetland as a cubic)
  - Separately calculated for RWs and NRWs at the sub-watershed scale
Wetland parameterization #2

- Normal wetland area and depth (Inundation map)
  - Selection of the inundation map taken at the weather condition most likely depicts the normal inundation pattern based on streamflow and Palmer drought index.
  - Normal surface area was estimated by calculating a weighted sum of inundation pixels (using inundation percentage as a weight), separately for RWs and NRWs at the sub-watershed scale (Huiran et al., 2016).
  - The normal depth is calculated using the same method used for the maximum depth.
  - Low normal volume for upland wetlands and great normal volume for downstream wetlands
Inundation pattern evaluation

<table>
<thead>
<tr>
<th>Description</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set A: Spatially-varying wetland parameters</td>
<td>2007 inundation map</td>
</tr>
<tr>
<td>Set B: Average of Set A</td>
<td>Uniform for all sub-watersheds</td>
</tr>
<tr>
<td>Set C: Parameters used in Liu et al. (2008)</td>
<td></td>
</tr>
</tbody>
</table>

Simulated RW inundation A  
Simulated RW inundation B  
Simulated RW inundation C

Exclusion of 2007 map

Comparison

Time-series inundation maps (7)  
A weighted sum of inundation pixels at sub-watershed scale

Observed inundation

Set A  
Set B  
Set C  
SWAT  
RWM  
No prediction on inundation areas within NRW
Wetland function evaluation

- Comparing wetland effects on streamflow between two sub-watersheds with different land use distribution

- The effect of wetland characteristics on peak flow reduction at a large storm event (when the greatest precipitation occurred during the simulation period)
Model calibration and validation

Daily simulation

<table>
<thead>
<tr>
<th></th>
<th>Period</th>
<th>NSE</th>
<th>RSR</th>
<th>PBIAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>NWET (Simulated streamflow without wetland module)</td>
<td>Calibration</td>
<td>0.424</td>
<td>0.758</td>
<td>-0.3</td>
</tr>
<tr>
<td></td>
<td>Validation</td>
<td>0.534</td>
<td>0.682</td>
<td>23.5</td>
</tr>
<tr>
<td>WET (Simulated streamflow with wetland module)</td>
<td>Calibration</td>
<td>0.461</td>
<td>0.733</td>
<td>-5.1</td>
</tr>
<tr>
<td></td>
<td>Validation</td>
<td>0.553</td>
<td>0.668</td>
<td>17</td>
</tr>
</tbody>
</table>

- Spatially-varying wetland parameters were used for WET.
Three sets of wetland parameters produce similar streamflow.
Inundation map vs Simulated inundation #1
Inundation map vs Simulated inundation #2
Inundation map vs Simulated inundation #3
Inundation map vs Simulated inundation #4
Land use effects on wetland

✓ Sub #1 dominated by forest

✓ Sub #4 dominated by agriculture

NWET: Simulation without wetland modules & WET: Simulation with wetland modules

<High-flow period>  <Low-flow period>  <At storm event>
Wetland effects on peak flow

✓ Comparing the relationship between peak flow reduction rate and wetland characteristics at 17 upstream sub-watersheds

- Peak flow reduction rate (%) = \( \frac{(NWET - WET)}{NWET} \times 100 \)
- CI: Confidence Interval & ***: statistical significance at the level of 0.01.
Conclusion

- Remote sensing data helped to set wetland parameters and evaluate wetland module performance.

- Integration of remote sensing data into a watershed model contributed to enhancing the model prediction on wetland hydrology and reducing model uncertainty.

- Wetlands were shown to be effective at regulating streamflow and mitigating peak flow.


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