Reducing equifinality
by using spatial wetness information and
reducing complexity in the SWAT-Hillslope model

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2015 SWAT Conference, Purdue University, USA, 14-16 October, 2015
Outline

- Brief description of the SWAT-Hillslope model
- Comparisons of SWAT-Hillslope and SWAT2012
- Parameter uncertainty in SWAT-Hillslope
- Equifinality vs. model complexity
- Conclusions and recommendations
Original SWAT

- Runoff determined by curve number
- HRU in SWAT is a combination of land use, soil, and slope
- All HRU connected with stream

SWAT_Hillslope

- Runoff when soil is saturated or low infiltration
- HRU in SWAT-Hillslope is a combination of land use, soil, slope and wetness class
  Wetness class consists of groups of similar topographic indices
- Perched water table source of interflow and connects wetness classes
Hydrological processes

Original SWAT

- Precipitation & snow melt
- Evapotranspiration
- Surface runoff (calculated based on Curve number)
- Lateral flow
- Recharge to deep aquifer
- GW
- River

SWAT_Hillslope

- Precipitation & snow melt
- Evapotranspiration
- Revap
- Infiltration excess SR (exceptional case) (calculated by Green-Ampt Method)
- Saturation excess runoff
- Lateral flow
- Aquifer recharge
- Perched aquifer
- GW
- River
Assign a value of EDC (effective depth coefficient) to each wetness class. This value represents the water storage capacity in each wetness class.
Case study: Town Brook watershed

Area: 37 km², in the Catskill Mountains of New York State.

Climate: humid with average temperature of 8°C and average annual precipitation of 1123mm.

Elevation: 493 to 989 m.

Soil: silty loam and silty clay loam

Land use: deciduous and mixed forests (60% of the watershed) in upper terrain; pasture and row crops (20%) and shrub land (18%) in lower terrain
## SWAT-Hillslope set up for Town Brook watershed

### Simple SWAT-Hillslope set ups

<table>
<thead>
<tr>
<th>SWAT-Hillslope setups</th>
<th>Wetness class</th>
<th>Soil type</th>
<th>Land use</th>
<th>Number of HRUs</th>
</tr>
</thead>
<tbody>
<tr>
<td>TB1</td>
<td>5</td>
<td>1</td>
<td>1 AGRL</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>average of dominant soil types</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TB2</td>
<td>5</td>
<td>5</td>
<td>1 AGRL</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 soil type for each wetness class</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TB3</td>
<td>5</td>
<td>5</td>
<td>3 Agriculture, Forest, Residence</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 soil type for each wetness class</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TB4</td>
<td>5</td>
<td>17</td>
<td>3 Agriculture, Forest, Residence</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td></td>
<td>detailed soil types</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TB5</td>
<td>5</td>
<td>17</td>
<td>11 detailed land use</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td></td>
<td>detailed soil types</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Prepare soil maps

- Source: SSURGO

- Several soil maps were prepared from simple to complex maps

1 soil type for the whole watershed

1 soil type for each wetness class
→ 5 soil types

SSURGO detailed soil types
→ 17 soil types
Prepare land use map

- Source: NYCDEP
- Several land use maps were prepared from simple to complex maps

1 land use for the whole watershed (AGRL)

3 dominant land uses: agriculture, forest and residence areas

All land uses included
Model calibration

Step 1: Calibrate snow melt parameters

Step 2: Calibrate flow parameters

Step 3: Adjust storage capacity of wetness classes

Method of calibration:

- Generate 10,000 random parameter sets by Monte Carlo sampling method

- Run 10,000 simulations with SWAT-Hillslope

- Choose the good performance parameter sets (NSE ≥ threshold)
Results and discussions
Performance of SWAT-Hillslope on flow simulation

Model performance guidelines (Moriasi et al., 2007)

<table>
<thead>
<tr>
<th>Performance rating</th>
<th>NSE</th>
<th>PBIAS (%)</th>
<th>RSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very good</td>
<td>$0.75 &lt; \text{NSE} \leq 1.00$</td>
<td>$\text{PBIAS} &lt; \pm 10$</td>
<td>$0.0 \leq \text{RSR} \leq 0.5$</td>
</tr>
<tr>
<td>Good</td>
<td>$0.65 &lt; \text{NSE} \leq 0.75$</td>
<td>$10 \leq \text{PBIAS} &lt; 15$</td>
<td>$0.5 &lt; \text{RSR} \leq 0.6$</td>
</tr>
<tr>
<td>Satisfactory</td>
<td>$0.50 &lt; \text{NSE} \leq 0.65$</td>
<td>$15 \leq \text{PBIAS} &lt; 25$</td>
<td>$0.6 &lt; \text{RSR} \leq 0.7$</td>
</tr>
<tr>
<td>Unsatisfactory</td>
<td>$\text{NSE} \leq 0.50$</td>
<td>$\text{PBIAS} \geq 25$</td>
<td>$\text{RSR} &gt; 0.7$</td>
</tr>
</tbody>
</table>

SWAT-Hillslope performance

Warming up
1998 - 2000

Calibration
2001 - 2007

Validation
2008 - 2012

<table>
<thead>
<tr>
<th>Period</th>
<th>Time steps</th>
<th>NSE</th>
<th>PBIAS</th>
<th>RSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration</td>
<td>Daily</td>
<td>0.66</td>
<td>11.13</td>
<td>0.58</td>
</tr>
<tr>
<td></td>
<td>Monthly</td>
<td>0.82</td>
<td>11.2</td>
<td>0.42</td>
</tr>
<tr>
<td>Validation</td>
<td>Daily</td>
<td>0.54</td>
<td>2.05</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td>Monthly</td>
<td>0.76</td>
<td>2.27</td>
<td>0.49</td>
</tr>
<tr>
<td>Validation</td>
<td>Daily</td>
<td>0.61</td>
<td>7.17</td>
<td>0.63</td>
</tr>
<tr>
<td>(excluding 2011)</td>
<td>Monthly</td>
<td>0.78</td>
<td>7.41</td>
<td>0.48</td>
</tr>
</tbody>
</table>
Performance of SWAT-Hillslope on flow simulation

Outlet discharge

Daily

Monthly
Flow components

SWAT-Hillslope

Lateral flow is the most significant contribution to streamflow.

SWAT2012

Surface runoff plays an important contribution, in high rainfall event.
Spatial distribution of annual surface runoff

SWAT-Hillslope Distribution of surface runoff follows topography and concentrates in locations with high topographic index

SWAT2012 The distribution of surface runoff predicted by SWAT2012 follows the distribution of land use
Performance of SWAT-Hillslope on flow simulation

Spatial distribution of saturated areas

- **SWAT2012**: no surface runoff. No rain from 28-30/04/2006
- **SWAT-Hillslope**: Interflow and predicted saturated areas in agreement with field observations

(a) Observations in 28-30/04/2006

(c) Rainfall in April 2006
Parameter uncertainty

<table>
<thead>
<tr>
<th>Name</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCHRG_PAF</td>
<td>Fraction of root zone percolation that recharges the perched aquifer</td>
</tr>
<tr>
<td>latA</td>
<td>Perched aquifer non-linear reservoir coefficient</td>
</tr>
<tr>
<td>latB</td>
<td>Perched aquifer non-linear reservoir coefficient</td>
</tr>
<tr>
<td>EFFPORFACTOR</td>
<td>Fraction of effective porosity that can hold water under saturated conditions</td>
</tr>
<tr>
<td>EDC_FACTOR</td>
<td>Calibration factor for adjusting edc values</td>
</tr>
</tbody>
</table>
Parameter uncertainty vs. model complexity

- Good parameters are broadly distributed within the ranges in models with different complexity
- These ranges are comparable in 5 models

<table>
<thead>
<tr>
<th>Number of “satisfactory” models (NSE ≥ 0.5)*</th>
<th>TB_1</th>
<th>TB2</th>
<th>TB3</th>
<th>TB4</th>
<th>TB5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of simulations = 10000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of “good” models (NSE ≥ 0.65)</td>
<td>23</td>
<td>534</td>
<td>435</td>
<td>160</td>
<td>128</td>
</tr>
<tr>
<td>Max NSE</td>
<td>0.66</td>
<td>0.68</td>
<td>0.67</td>
<td>0.66</td>
<td>0.66</td>
</tr>
</tbody>
</table>

| Range of good parameters                     |      |      |      |      |      |
| RCHRG_PAF                                   | 0.66 - 0.89 | 0.6 - 0.9 | 0.6 - 0.9 | 0.6 - 0.9 | 0.6 - 0.9 |
| Lata                                        | 0.007 - 0.08 | 0.001 - 0.1 | 0.001 - 0.1 | 0.001 - 0.1 | 0.003 - 0.1 |
| Latb                                        | 1.33 - 1.92 | 1.06 - 2.32 | 1.17 - 2.32 | 1.20 - 2.32 | 1.20 - 2.11 |
| Alpha bf                                    | 0.20 - 0.95 | 0.0 - 1.0 | 0.0 - 1.0 | 0.02 - 0.99 | 0.07 - 0.99 |
| GW_delay                                    | 14 - 193 | 3 - 200 | 0.2 - 199 | 7 - 198 | 7 - 198 |
| EFFPORFACTOR                                | 0.24 - 1.0 | 0.0 - 1.0 | 0.0 - 1.0 | 0.03 - 1.0 | 0.03 - 1.0 |
| EDC_FACTOR                                  | 1.3 - 3.9 | 0.67 - 5.0 | 0.97 - 5.0 | 0.97 - 5.0 | 0.97 - 4.76 |
| EPCO                                        | 0.02 - 0.70 | 0.0 - 1.0 | 0.0 - 1.0 | 0.02 - 1.0 | 0.02 - 1.0 |
| ESCO                                        | 0.005 - 0.6 | 0.0 - 1.0 | 0.0 - 0.96 | 0.005 - 0.96 | 0.005 - 0.96 |
| CANMX                                       | 1.14 - 4.92 | 0.02 - 5.0 | 0.03 - 5.0 | 0.68 - 4.97 | 0.80 - 4.97 |
| SURLAG                                      | 2.4 - 22.1 | 0.5 - 24 | 0.1 - 24 | 0.4 - 23.9 | 0.4 - 23.8 |

Increasing model complexity does not improve model performance
## Equifinality vs. model complexity

<table>
<thead>
<tr>
<th>SWAT-Hillslope model setups</th>
<th>TB_1</th>
<th>TB2</th>
<th>TB3</th>
<th>TB4</th>
<th>TB5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of “satisfactory” models (NSE ≥ 0.5)*</td>
<td>2580</td>
<td>3081</td>
<td>2735</td>
<td>2566</td>
<td>2564</td>
</tr>
<tr>
<td>Total number of simulations = 10000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% of measurements falling into “satisfactory” uncertainty bounds</td>
<td>83.9%</td>
<td>84.2%</td>
<td>84.1%</td>
<td>82.5%</td>
<td>82.2%</td>
</tr>
<tr>
<td>Number of “good” models (NSE ≥ 0.65)*</td>
<td>23</td>
<td>534</td>
<td>435</td>
<td>160</td>
<td>128</td>
</tr>
<tr>
<td>% of measurements falling into uncertainty bounds in calibration period</td>
<td>44.2%</td>
<td>66.4%</td>
<td>65.0%</td>
<td>58.1%</td>
<td>57.3%</td>
</tr>
<tr>
<td>% of measurements falling into uncertainty bounds in validation period</td>
<td>40.6%</td>
<td>53.4%</td>
<td>42.3%</td>
<td>43.8%</td>
<td>43.2%</td>
</tr>
</tbody>
</table>
- **TB2 setup** gave the best results among all set ups: achieved the highest NSE, captured the highest percentage of measurements both in calibration and validation periods.

- **TB1 setup** with homogenous soil and land use gave the worst performance: captured the lowest percentage of measurements because of over-simplification.

- The most complicated set up did not give the best results.
Uncertainty of modeled result (results from TB2 setup)

Streamflow

Daily

Monthly
Uncertainty of modeled result (results from TB2 setup)

Probability of saturation

<table>
<thead>
<tr>
<th>Wetness 1</th>
<th>68.3 - 100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wetness 2</td>
<td>6.9 – 86.3</td>
</tr>
<tr>
<td>Wetness 3</td>
<td>0.3 - 75</td>
</tr>
<tr>
<td>Wetness 4</td>
<td>0</td>
</tr>
<tr>
<td>Wetness 5</td>
<td>0</td>
</tr>
</tbody>
</table>

After filtering by comparing with the observed saturated areas in 28-30 April 2006

Number of good parameter sets

534

Number of good parameter sets

150

More information and observations will help to choose the most reasonable parameter sets and reduce the uncertainty of modeled results
Conclusions and recommendations

- SWAT-Hillslope successfully simulates separately the infiltration-excess runoff and saturation excess runoff.
- SWAT-Hillslope performed well in simulating streamflow as well as the spatial distribution of saturated areas.
- As in many hydrological models, equifinality is also a problematic issue in SWAT-Hillslope.
Conclusions and recommendations

- The testing in models with different complexity revealed that the most complicated model does not necessarily give the better simulated results.

- Reducing the model complexity by simplifying soil and land use types can increase the model performance, however, we should be cautious to not over-simplify.

- Reducing the model complexity does not aid in reducing equifinality. However, using all available spatial information and observations on locations of saturated soils can aid in finding the most realistic parameter set and in reducing uncertainty.
Thank you
for your attention
Description of the SWAT-Hillslope model

Lateral flow is calculated based on the depth of water in perched aquifer at the beginning of the time step (the result from previous time step) and the recharge to perched aquifer in the current time step by a non linear reservoir equation:

\[ \text{latqsub} = \text{lata} \times \left( (\text{sub_perchst2}(sb) - \text{perchst_datum}) + \text{sub_rchrgpa}(sb) \right)^{\text{latb}} \]

\[ \text{Available}\quad \text{perched storage}\]

\[ \text{Recharge}\]

\[ \text{Lata, latb are parameters for calibration}\]
Watershed delineation

✓ Resolution: DEM 10m x 10m
✓ Geographic coordinate system: WGS_1984
✓ DEM is projected to the coordinate system: NAD 1983 Zone 18N

Delineate the watershed based on the location of outlet
Creating wetness map: based on topographic index

- Calculate topographic index

\[
\lambda = \ln\left(\frac{\alpha}{\tan(\beta) K_s D}\right)
\]

- \(\lambda\): soil topographic index (STI), unit: \(\ln(d \text{ m}^{-1})\)
- \(\alpha\): upslope contributing area per unit contour length (m)
- \(\tan(\beta)\): the local surface topographic slope
- \(K_s\): mean saturated hydraulic conductivity of the soil (m d\(^{-1}\))
- \(D\): soil depth (m)
Creating wetness map: based on topographic index

✓ Classify to wetness classes

(Agnew et al., 2006)
Weather input

Precipitation, temperature data is available in PRISM gridded data.

Data for the whole watershed which is assumed to be taken at the centroid of the watershed is interpolated from data of surrounding stations by inverse distance weighting method.