The simulation of watershed-scale effectiveness of agricultural best management practices in a drinking water resource area of Beijing, China

Jiali Qiu
Ph.D candidate
School of Environment
Beijing Normal University
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1. Non-point source pollution

Non-point source pollution from agricultural area have a significant impact on water quality.

Main source:
2. The development of BMPs

Best management practices (BMPs) are defined as the state-of-the-art management practices that help prevent or reduce NPS pollution to a level compatible with water quality goals.

- Structural BMPs
- Non-structural BMPs
3. Models for assessing BMPs

<table>
<thead>
<tr>
<th>Models</th>
<th>Temporal Resolution</th>
<th>Spatial Representation</th>
<th>Overland Flow Routing</th>
<th>Overland Sediment Routing</th>
<th>Channel Processes</th>
<th>Developer</th>
</tr>
</thead>
<tbody>
<tr>
<td>SWAT</td>
<td>Continuous; Daily or sub-daily time steps.</td>
<td>Sub-basins or further hydrologic response units defined by soil and land use/land cover.</td>
<td>SCS-CN method for infiltration and peak flow rate by modified Rational formula.</td>
<td>MUSLE represented by runoff volume, peak flow rate, and USLE factors.</td>
<td>Channel degradation and sediment deposition process including channel-specific factors.</td>
<td>USDA</td>
</tr>
<tr>
<td>AGNPS</td>
<td>Storm-event; One storm duration as a time step.</td>
<td>Cells of equal size with channels included.</td>
<td>SCS-CN method for infiltration, and flow peak using a similar method with SWAT.</td>
<td>USLE for soil erosion and sediment routing through cells with n, USLE factors to be concerned with.</td>
<td>Included in overland cells.</td>
<td>USDA</td>
</tr>
<tr>
<td>AnnAGNPS</td>
<td>Continuous; daily or sub-daily time steps.</td>
<td>Cells with homogeneous soil and land use.</td>
<td>SCS-CN method for infiltration and TR-55 method for peak flow.</td>
<td>RUSLE to generate soil erosion daily or user-defined runoff event.</td>
<td>Channel degradation and sediment deposition with Modified Einstein equation and Bagnold equation.</td>
<td>USDA</td>
</tr>
<tr>
<td>HSPF</td>
<td>Continuous; variable constant steps (from 1 min up to 1 day).</td>
<td>Pervious and impervious land areas, stream; hydrologic response units.</td>
<td>Philip’s equation for infiltration.</td>
<td>Rainfall splash and wash off of detached sediment calculated by an experimental non-liner equation.</td>
<td>Non-cohesive and cohesive sediment transport.</td>
<td>USGS and USEPA</td>
</tr>
</tbody>
</table>

3. Models for assessing BMPs

Representation of BMPs

The types of agricultural BMPs that can be assessed by different watershed models:

- Contour farming
- Strip cropping
- Rotation
- Nutrient management
- Tillage management
- Residue management
- Grazing management
- Cover crop
- Cropland conversion
- Terrace
- Grassed waterway
- GSS
- Pond and sediment basin
- Filter strip
- SCS

GSS: Grade stabilization structure; SCS: Stream channel stabilization
4. Watershed description

Miyun Watershed is the water source protection area of Miyun Reservoir, which is one of the biggest reservoirs in North China, supplying Beijing residents with potable water.
PART TWO

SWAT model description
1. SWAT description

- The Soil and Water Assessment Tool (SWAT) was used to simulate the flow and nutrient loads in the watershed scale.
- The SWAT-CUP program was used to calibrate and verify the model parameters.
1. SWAT description: hydrology

The land phase of the hydrologic cycle is based on the water balance equation:

\[ SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}) \]

### Runoff volume

### Peak runoff rate

### Base flow

#### SCS curve number procedure:

\[ Q_{surf} = \frac{(R_{day} - I_a)^2}{(R_{day} - I_a + S)} \]

\[ S = \frac{25400}{CN} - 254 \]

#### Modified rational method:

\[ q_{peak} = \frac{C \cdot i \cdot Area}{3.6} \]

\[ C = \frac{Q_{surf}}{R_{day}} \]

#### Steady-state response of base flow to recharge:

Base flow is allowed to enter the reach only if the amount of water stores in the shallow aquifer exceeds a threshold value specified by the user, \( aq_{shthr,q} \):

\[ Q_{gw} = \frac{8000 \cdot K_{sat} \cdot h_{wtbl}}{L_{gw}^2} \]
1. SWAT description: nutrients

**Nitrate:** The concentration of nitrate in the mobile water fraction is calculated:

\[
conc_{\text{NO}_3,\text{mobile}} = \frac{NO_3_{,\text{ly}} \cdot \left\{ 1 - \exp \left[ \frac{-w_{\text{mobile}}}{(1 - \theta_e) \cdot SAT_{\text{ly}}} \right] \right\}}{w_{\text{mobile}}}
\]

\[w_{\text{mobile}} = Q_{\text{surf}} + Q_{\text{lat,ly}} + w_{\text{perc,ly}}\]

**Organic N:** The amount of organic N transported with sediment to the stream is calculated with a loading function:

\[orgN_{\text{surf}} = 0.001 \cdot conc_{\text{orgN}} \cdot \frac{sed}{area_{\text{hru}}} \cdot \varepsilon_{N:sed}\]

**Solution phosphorus:** the amount transported in surface runoff is:

\[P_{\text{surf}} = \frac{P_{\text{solution, surf}} \cdot Q_{\text{surf}}}{\rho_b \cdot depth_{\text{surf}} \cdot k_{d,\text{surf}}}\]

**Organic & mineral P** transported with sediment to the stream is calculated:

\[sedP_{\text{surf}} = 0.001 \cdot conc_{\text{sedP}} \cdot \frac{sed}{area_{\text{hru}}} \cdot \varepsilon_{P:sed}\]
PART THREE

BMP tool description
The common principle of BMPs representation is to depict the change in watershed processes and the response of water quality under or without BMPs. By changing model inputs or parameter values according to *conservation practices modelling guide*. Outputs from a particular BMP scenario were annual load change of sediment, total phosphorus (TP) and total nitrogen (TN).
2. BMP modelling

**BMP modelling**

<table>
<thead>
<tr>
<th>BMP</th>
<th>Parameters</th>
<th>Specific Module</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contouring</td>
<td>CN2, USLE_P</td>
<td>.OPS</td>
</tr>
<tr>
<td>Strip cropping</td>
<td>CN2, n, USLE_P, USLE_C</td>
<td>.OPS</td>
</tr>
<tr>
<td>Residue management</td>
<td>CN2, n, USLE_C</td>
<td>.OPS</td>
</tr>
<tr>
<td>Tillage management</td>
<td>CN2, EFFMIX, DEPTIL</td>
<td>.MGT</td>
</tr>
<tr>
<td>Filter strip</td>
<td>VFS routine (FILTER_RATIO, TILTER CON, FILTER_CH) or FILTERW</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CH_depth, CH_width, CH_COV, CH_n</td>
<td>.OPS</td>
</tr>
<tr>
<td></td>
<td>CH_EROD, CH_N2</td>
<td>.PND</td>
</tr>
<tr>
<td></td>
<td>PND_FR, PND_PSA and PND_K</td>
<td>.PND</td>
</tr>
</tbody>
</table>

**SWAT model allows information about these measures to be modified by scheduling the amount, timing and period of agricultural activities.**

**Notes:**
- EFFMIX: The mixing efficiency of a tillage options
- EFFTIL: Depth of mixing caused by tillage options

**Land management**

- Converting cropland to forest over $15^\circ$ slope and $25^\circ$ slope

**Nutrient management**

- Converting cropland to forest over $15^\circ$ slope and $25^\circ$ slope
- 20% and 30% fertilizer reduction

**Structural BMPs**

- 20% and 30% fertilizer reduction
- Grassed waterway, filter strip, sediment basin, etc.
PART FOUR

Results and discussion
## 1. Parameter sensitivity

<table>
<thead>
<tr>
<th>Variable</th>
<th>Parameter</th>
<th>Description</th>
<th>Lower limit</th>
<th>Upper limit</th>
<th>Conversion</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLOW</td>
<td>SOL BD</td>
<td>Threshold water level in the shallow aquifer for the base flow</td>
<td>0</td>
<td>500</td>
<td>v</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>GWQMN</td>
<td>Threshold water level in the shallow aquifer for the base flow</td>
<td>0</td>
<td>5000</td>
<td>v</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>SOL_BD</td>
<td>Depth from soil surface to the bottom of the layer</td>
<td>-0.01</td>
<td>500</td>
<td>v</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>CH_K2</td>
<td>Threshold hydraulic conductivity of the first layer</td>
<td>0</td>
<td>0.8</td>
<td>F</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>REVAPMN</td>
<td>Threshold hydraulic conductivity of the first layer</td>
<td>0</td>
<td>0.8</td>
<td>F</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>SOL BD</td>
<td>Threshold water level in the shallow aquifer for the base flow</td>
<td>0</td>
<td>5000</td>
<td>v</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>SOL Z</td>
<td>Depth from soil surface to the bottom of the layer</td>
<td>-1</td>
<td>1</td>
<td>r</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>TNSRCH</td>
<td>Maximum canopy storage</td>
<td>0</td>
<td>100</td>
<td>v</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>SOL AWC</td>
<td>Plant uptake compensation factor</td>
<td>0</td>
<td>1</td>
<td>v</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>RCHRG_DP</td>
<td>Fraction of transmission losses from main channel that enter deep aquifer</td>
<td>0</td>
<td>1</td>
<td>v</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>SOL_SOLP</td>
<td>Initial labile (soluble) P concentration in the soil layer</td>
<td>0</td>
<td>100</td>
<td>v</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>BC4</td>
<td>Rate constant for decay of organic phosphorus to dissolved phosphorus</td>
<td>0</td>
<td>0.01</td>
<td>v</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>BCP</td>
<td>Deep aquifer</td>
<td>0</td>
<td>0.7</td>
<td>v</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>RCHRG_DP</td>
<td>Deep aquifer water</td>
<td>0</td>
<td>0.1</td>
<td>v</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>SOL AWC</td>
<td>Available water capacity of the soil layer</td>
<td>0</td>
<td>500</td>
<td>v</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>CH N2</td>
<td>Michaelis-Menten half-saturation constant for nitrogen (1/day)</td>
<td>0</td>
<td>0.01</td>
<td>v</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>SOL ORGN</td>
<td>Initial humic organic nitrogen in the soil layer</td>
<td>0</td>
<td>100</td>
<td>v</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>NPERCO</td>
<td>Nitrogen percolation coefficient</td>
<td>0</td>
<td>0.01</td>
<td>v</td>
<td>18</td>
</tr>
</tbody>
</table>

**Notes:**
- **Variable:** The column header indicates the variable name.
- **Parameter:** The description of the variable.
- **Description:** A brief description of the parameter.
- **Lower limit:** The lower range value.
- **Upper limit:** The upper range value.
- **Conversion:** The conversion method.
- **Rank:** The rank of the parameter.
2. Parameter calibration and validation

<table>
<thead>
<tr>
<th>Variable</th>
<th>Index</th>
<th>Calibration</th>
<th>Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow</td>
<td>$R^2$</td>
<td>0.821</td>
<td>0.772</td>
</tr>
<tr>
<td>Ens</td>
<td></td>
<td>0.776</td>
<td>0.693</td>
</tr>
<tr>
<td>TN</td>
<td>$R^2$</td>
<td>0.770</td>
<td>0.701</td>
</tr>
<tr>
<td>Ens</td>
<td></td>
<td>0.721</td>
<td>0.488</td>
</tr>
<tr>
<td>TP</td>
<td>$R^2$</td>
<td>0.812</td>
<td>0.773</td>
</tr>
<tr>
<td>Ens</td>
<td></td>
<td>0.788</td>
<td>0.528</td>
</tr>
</tbody>
</table>
2. Parameter calibration and validation

<table>
<thead>
<tr>
<th>Variable</th>
<th>Index</th>
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<th>Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow</td>
<td>$R^2$</td>
<td>0.830</td>
<td>0.703</td>
</tr>
<tr>
<td>Ens</td>
<td></td>
<td>0.821</td>
<td>0.508</td>
</tr>
<tr>
<td>TN</td>
<td>$R^2$</td>
<td>0.816</td>
<td>0.710</td>
</tr>
<tr>
<td>Ens</td>
<td></td>
<td>0.714</td>
<td>0.444</td>
</tr>
<tr>
<td>TP</td>
<td>$R^2$</td>
<td>0.803</td>
<td>0.780</td>
</tr>
<tr>
<td>Ens</td>
<td></td>
<td>0.568</td>
<td>0.512</td>
</tr>
</tbody>
</table>
3. Spatial distribution of pollution
3. Spatial distribution of pollution
4. The loads from different land uses

AGRL, Agricultural Land-Generic
FRST, Forest-Mixed
PAST, Pasture
SWRN, Southwestern US (Arid) Range or vacant land
UIDU, Industrial
URMD, Residential-Medium Density
URML, Residential-Med/Low Density
5. The loads from different soil types

- Arc, Calcaric Arenosols
- CMc, Calcaric Cambisols
- CMe, Eutric Cambisols
- FLc, Calcaric Fluvisols
- GRh, Haplic Greyzems
- KSI, Luvic Kastanozems
- LVg, Gleyic Luvisols
- LVh, Haplic Luvisols
- LVk, Calcic Luvisols
- RGe, Eutric Regosols
- RGc, Calcaric Regosols
4. Temporal distribution of pollution

**FLOW-PREC**: $R^2 = 0.778$

**TN-PREC**: $R^2 = 0.396$

**TP-PREC**: $R^2 = 0.465$
Efficiency of structural BMPs were better than non-structural BMPs.

Lower efficiencies in Bai River.

The efficiency of each BMP varied in the different sub-basins.
The high content of nitrogen in the fertilizer resulted in the non-structural BMPs having better effects on nitrogen than on phosphorus.

Structural BMPs have similar effect on nitrogen and phosphorus, even have better efficiency for P.

CCF: Converting cropland to forest
Conclusions and Outlook

1. The SWAT model has good applicability for NPS pollution simulation in this area. The NPS pollution exhibited apparent temporal-spatial heterogeneity. The pollutant loads were positively correlated with the annual rainfall amounts and with agricultural activities.

2. The efficiency of each BMP varied in the different sub-basins. The structural BMPs such as filter strip, grassed waterways and constructed wetland was better than that of non-structural BMPs such as converting cropland to forest, soil testing and fertilizer recommendation and conservation tillage.

3. Further research is required to analyze the influence factors on BMP efficiency and to select a preferred set of BMPs that would result in the greatest reduction in pollutant loads for the least cost to achieve the water environmental control targets.
Thanks for Attention

Jiali Qiu
Ph.D candidate
School of Environment
Beijing Normal University
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