Impact of critical source area on AnnAGNPS simulation

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ABSTRACT

The objective of this paper is to study the impact of critical source area (CSA) within an Annualized Agricultural Non-Point Source pollution models (AnnAGNPS) simulation at medium- large watershed scale. The impact of CSA on terrain attributes is examined by comparing six sets of CSA (0.5, 1, 2, 4, 6 and 8 km²). The accuracy of AnnAGNPS stimulation on runoff, sediment and nutrient loads on these sets of CSA is further suggested in this paper. The results are as followed: (1) CSA has little effect on watershed area, and terrain altitude. The number of cell and reach decreases with the increase of CSA in power function regression curve. (2) The variation of CSA will lead to the uncertainty of average slope which increase the generalization of land characteristics. At the CSA range of 0.5–1 km², there is little impact of CSA on slope. (3) Runoff amount does not vary so much with the variation of CSA whereas soil erosion and total nitrogen (TN) load change prominently. An increase of sediment yield is observed firstly then a decrease following later. There is evident decrease of TN load, especially when CSA is bigger than 6 km². Total phosphorus load has little variation with the change of CSA. Results for Dage watershed show that CSA of 1 km² is desired to avoid large underestimates of loads. Increasing the CSA beyond this threshold will affect the computed runoff flux but generate prediction errors for nitrogen yields. So the appropriate CSA will control error and make simulation at acceptable level.

Key words | AnnAGNPS simulation, critical source area (CSA), non-point source pollution loading, terrain attributes

INTRODUCTION

Non-point source pollution is complex and occurs on the land surface. Prominent discrepancies in model simulation can occur with scale change of watershed subdivision in models (Vieux & Needham 1995; Bloeschl & Sivapalan 1995; Arnold et al. 1998; Ahmadzadeh & Petrou 2001; Chen et al. 2006). In the Annualized Agricultural Non-Point Source pollution (AnnAGNPS) model, a cell is the basic unit for watershed runoff and pollutant load calculation. The discretization of watershed network is determined by the critical source area (CSA) and minimum source channel length (MSCL). In general, the CSA is defined as the minimum catchment area required by a channel for permanent exist where is considered as the source area of rivers (Beven & Kirkby 1979; Quinn et al. 1991; Brannan & Hamlett 1998). The CSA is commonly presumed as constant when extracting stream network by using digital elevation model (DEM). It has been recognized that discretization scale significantly affects watershed model results, with respect to both hydrology and water quality (Brown et al. 1993; Farajall & Vieux 1995; Brasington & Richards 1998; Callow et al. 2007; Tian et al. 2009). In fact, there are many factors influencing the CSA, such as slope, soil, land use, climate and vegetation. Theoretically, the small CSA as possible is required to represent the practical situation and to assure the precision of model stimulation. However, the smaller CSA will lead to the more cells and the more calculated amount for model. So, the suitable CSA will balance the accuracy of stimulation and calculated data amount. The spatial extent of input parameter aggregation has been studied previously to have substantial impact on model outputs (FitzHugh & Mackay 2000; Jha et al. 2004; Huang et al. 2009). Such results have attributed to the impacts of increasing amounts of aggregation on the distribution of overland soil, land use, and terrain parameters.
(Zhang & Montgomery 1994; Chaplot et al. 2000, 2004, 2005; Chen & Mackay 2004; Kang et al. 2004; Xu et al. 2007). The objective of this paper is to study the impact of CSA within an AnnAGNPS Model applied to simulate runoff, sediment, total nitrogen (TN), and total phosphorus (TP) loads for a small watershed – the Dage subwatershed of the Chaohe river basin, China.

**THE STUDY AREA**

Miyun Reservoir is the most important source of drinking water supply for Beijing. It is situated in Miyun County, which is within the northern mountain area of Beijing Autonomous Municipality. Its upper watershed includes two perennial rivers (Chaohe River and Baihe River) and five seasonal ephemeral rivers. The watershed flows across nine counties of Beijing Autonomous Municipality and Hebei Province. The total watershed area is 14,871 km² of which 1,400 km² is in Miyun County (Figure 1). Due to strict control of point source pollution by banning any kind of plant effluents in the second-class protection areas, nitrogen and phosphorus loads are mainly from non-point sources. The eutrophication trend has become an important factor in the degradation of the water quality of Miyun Reservoir. Currently, the water quality of Miyun Reservoir is mainly mesotrophic.

Research revealed that non-point sources contributed 75% TN and 94% TP, respectively (Wang et al. 2003). The region has a continental climate. The average annual precipitation is 660 mm and of this amount, 76.5% usually falls from July through September (Wang et al. 2001).

The studies area – Dage watershed is situated at the headwater of Chaohe River, with a total area of 1,876 km². The elevations are from 623 m to 2,213 m with a decreasing trend from northwest to southeast. Forest and grass land are two major land use types in the watershed, accounting for 44.24 and 27.64% of the total land area, respectively. Major soil types on the watershed are brown earth (over 50%) and umber.

**MATERIALS AND METHODS**

**Brief description of AnnAGNPS model**

AnnAGNPS model is a parameter distributed model at watershed scale developed by USDA – ARS (United States Department of Agriculture – the Agricultural Research Service) and NRCS (The Natural Resources Conservation Service) including runoff, soil erosion and chemical transport models. The calculation of Hydrological model is based on water balance Equation (1) and the Soil Conservation Services Curve Number (SCS-CN) Equations (2) and (3) (Bingner & Theurer 2005). Sediment load is calculated by Revised Universal Soil Loss Equation (4).

\[
SM_{t+1} = SM_t + \left( W_I + Q_t + PERC_t + ET_t + Q_{lat} + Q_{tile} \right)/Z
\]  

where \( SM_t \) is moisture content for each soil layer at beginning of time period (fraction), \( SM_{t+1} \) is moisture content for each soil layer at end of time period (fraction), \( W_I \) is water input, consisting of precipitation or snowmelt plus irrigation water (mm), \( Q_t \) is surface runoff (mm), \( PERC_t \) is percolation of water out of each soil layer (mm), \( ET_t \) is potential evapotranspiration (mm), \( Q_{lat} \) is subsurface lateral flow (mm), \( Q_{tile} \) is tile drainage flow (mm), \( Z \) is thickness for soil layer (mm), and \( t \) is the time period.

\[
Q = (W_I - 0.2S)^2/(W_I + 0.8S)
\]  

\[
S = 25,400/CN - 254
\]

where \( Q \) is runoff (mm), \( W_I \) is water input to soil (mm), \( S \) is the potential maximum retention; \( CN \) is curve number which is a function of land use, soil, management, and hydrologic condition. In SCS model, soils are defined by 4 groups based on their runoff potential-low, moderately
low, moderately high and high.

\[ A = R \cdot K \cdot L \cdot S \cdot C \cdot P \]  \hspace{1cm} (4)

where \( A \) is estimated average soil loss in tons per acre per year, \( R \) is rainfall-runoff erosivity factor, \( K \) is soil erodibility factor, \( L \) is slope length factor, \( S \) is slope steepness factor, \( C \) is cover-management factor, \( P \) is support practice factor.

**Parameters of model and data analysis**

Some parameters are influenced strongly by CSA, such as watershed area, cell number, cell slope and cell elevation. In this paper, reach number, reach slope, reach elevation and reach length, runoff, sediment yield and TN, TP loading are selected to study the impact of CSA on model simulation.

The studied area has nearly sole soil type, and uncomplicated geomorphic characteristics and land use; The CSA is set as seven conditions from 0.5 to 8 km\(^2\) (see Table 1).

DEM data is from 30 m × 30 m raster data of 1: 50,000 topographic map. By running TopAGNPS module of AnnAGNPS Arcview Interface, the converged networks including cells and reaches are divided according to different CSA settings and the studied parameters are calculated. Based on land use data of the year 1995, soil data and metrological data (from the year 1990 to 2000), the impact of CSA on nonpoint source pollution loading are studied.

**RESULTS AND DISCUSSION**

**Impacts of different CSA on terrain parameters of cells and reaches**

According to the values of CSA and MSCL of AnnAGNPS model (Table 1), the watershed delineation is shown in Figure 2.

Compared on the area of watershed at different CSA settings, the result is shown in Table 2.

It shows that there is little impact of CSA on watershed area. The area is almost same at different CSA settings, except the little variance at CSA = 2 km\(^2\) and 3 km\(^2\). These tiny differences may be explained by the selection of outlet, but unrelated with CSA and MSCL.

Statistics analysis on the elevation of cells and reaches from different CSA indicates that there is little impact on the minimum elevation whereas there is decreasing trend of maximum elevation with CSA. There is a slight variance of average elevation of cells and reaches (see Table 3).

As seen from Figure 2, the stream network becomes sparser with the increase of CSA value. That means the number of catchment became fewer.

There is regular variance of CSA and the number of cell and reach (See Table 2). The fitted regression equation is as followed:

\[ y_1 = 2.473.702x - 1.0179 \quad R^2 = 0.9987 \]

**Calibration and validation of model**

The hydrological flow and sediment data from the year of 1980–1990 at Dage gauge station are used for model calibration and validation by adjusting some parameters. Table 1 is the comparison of simulated load of flow and sediment and measured ones.

Regarding to hydrological simulation, the simulated values of annual mean flow are much closer to measured ones during the normal flow years and high flow years. In the year of 1984 with very low flow, the stimulated flow varies greatly. There is similar trend for sediment simulation. During the normal flow years and high flow years, there are better simulated results. However, the contributions of sediment and nutrient loads during low flow periods are very small for annual load. So AnnAGNPS model may be used for simulation of non-point source pollution in this research area after calibration and validation.

<table>
<thead>
<tr>
<th>Year</th>
<th>Measured flow (mm)</th>
<th>Stimulated flow (mm)</th>
<th>Measured sediment (t)</th>
<th>Stimulated sediment (t)</th>
<th>Precipitation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980</td>
<td>33.25</td>
<td>10.82</td>
<td>20.80</td>
<td>25.38</td>
<td>398.60</td>
</tr>
<tr>
<td>1981</td>
<td>29.87</td>
<td>10.33</td>
<td>62.60</td>
<td>62.65</td>
<td>384.10</td>
</tr>
<tr>
<td>1982</td>
<td>70.15</td>
<td>83.13</td>
<td>142.00</td>
<td>96.50</td>
<td>532.60</td>
</tr>
<tr>
<td>1983</td>
<td>28.18</td>
<td>13.91</td>
<td>38.90</td>
<td>29.91</td>
<td>385.80</td>
</tr>
<tr>
<td>1984</td>
<td>24.18</td>
<td>4.08</td>
<td>86.60</td>
<td>20.53</td>
<td>293.00</td>
</tr>
<tr>
<td>1985</td>
<td>29.44</td>
<td>21.37</td>
<td>134.00</td>
<td>86.81</td>
<td>433.90</td>
</tr>
<tr>
<td>1986</td>
<td>51.08</td>
<td>62.91</td>
<td>240.00</td>
<td>165.24</td>
<td>534.70</td>
</tr>
<tr>
<td>1987</td>
<td>46.26</td>
<td>59.92</td>
<td>145.00</td>
<td>67.50</td>
<td>557.40</td>
</tr>
<tr>
<td>1988</td>
<td>46.49</td>
<td>48.84</td>
<td>62.70</td>
<td>57.11</td>
<td>409.30</td>
</tr>
<tr>
<td>1989</td>
<td>28.55</td>
<td>18.77</td>
<td>45.30</td>
<td>53.73</td>
<td>416.50</td>
</tr>
<tr>
<td>1990</td>
<td>39.68</td>
<td>51.25</td>
<td>109.00</td>
<td>84.03</td>
<td>624.30</td>
</tr>
</tbody>
</table>
\[ y_2 = 1.006.725x - 1.0272 \quad R^2 = 0.9988 \]

In which, \( y_1, y_2 \) represents the number of cell and reach after regression, \( x \) is the value of CSA. The determination coefficient \( R^2 \) are more than 0.998, which means these regressions can represent the varied pattern of the number of cell and reach with CSA.

Table 4 shows the variance of cell slope at different CSA. It can be seen that the maximum slope of cell decreases firstly with the increase of CSA, and then tends to steady. The mean slope has tiny variance whereas the minimum slope varies greatly.

For further clarification on the effect of DEM resolution on different slope grades, seven grades of cell slope such as 0–5 (grade 1), 5–10 (grade 2), 10–15 (grade 3), 15–20 (grade 4), 20–25 (grade 5), 25–30 (grade 6), 30–35 (grade 7) and >35 (grade 8) are classified according to the critical slope grading (Tang et al. 2005). The area percentages of different slope grades are recalculated according to this classification and shown in Figure 3.

As shown by Figure 3, the percentage of lower slope (grades 1, 2) and higher slope (grades 7, 8) are smaller than the medium slope (grades 3–5), especially for grade 4; There is clear increase of slope area with CSA. The cell number decreases sharply when cell slope >30°. It indicates that steep slope is generalized with increase of CSA. In general, the increase of CSA causes the area loss of steep and gentle slope whereas the area addition of medium slope.

With the increase of CSA from 0.5 to 1 km², the percentage of lower slope (grades 1, 2) and higher slope (grades 7, 8)
increase slightly; While the percentages of the medium slope (grades 3–5) keep almost the same. That means that there is little effect of CSA to cell slope at CSA range from 0.5 to 1 km².

From Figure 2, we can seen that the smallest CSA as possible may represent the practical situation and to assure the precision of model stimulation. However, the smaller CSA will lead to the more cells and the more calculated amount for model. So, the suitable CSA will influence the accuracy of stimulation.

In this study, CSA = 1 km² and MSCL = 200 are chosen for AnnAGNPS model stimulation so that the predicted results can represent the practical situation closely and the calculated amount of model stimulation is lessened as well.

**Impacts of different CSA on stimulated results of non-point source pollution**

After the calibration and validation of AnnAGNPS model, the stimulated results are showed on Table 5 based on the hydrological data of the year 1988.

There is little influence on stimulated runoff whereas simulated sediment increases firstly, then with a decreasing trend. That may be resulted from two factors. Slope of cell and reach decrease gradually while CSA increases. That will lead to decrease of the sediment loading. In addition,
the length of stream is getting short with CSA increase, so the transfer route of sediment becomes short which lead to the increase of sediment loading. TN loading decrease with the increase of SCA and TP has slighter variance. That may be related with the slope generalization.

CONCLUSIONS

The results are as followed: (1) CSA has little effect on watershed area, and terrain altitude. The number of cell and reach decreases with the increase of CSA in power function regression curve. (2) The variation of CSA will lead to the uncertainty of average slope which increase the generalization of land characteristics. At the CSA range of 0.5–1 km², there is little impact of CSA on slope. (3) Runoff amount does not vary so much with the variation of CSA whereas soil erosion and TN load change prominently. An increase of sediment yield is observed firstly then a decrease following later. TN load decreases evidently especially when CSA is bigger than 6 km². TP load has little variation with CSA does not vary so much with the variation of CSA whereas soil erosion and TN load change prominently. An increase of sediment yield is observed firstly then a decrease following later. TN load decreases evidently especially when CSA is bigger than 6 km². TP load has little variation with the variation of CSA.

<table>
<thead>
<tr>
<th>CSA (km²)</th>
<th>Runoff (mm/year)</th>
<th>Sed (mg/ha/year)</th>
<th>TN (mg/ha/year)</th>
<th>TP (mg/ha/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>46.05</td>
<td>3.82</td>
<td>7.88</td>
<td>0.61</td>
</tr>
<tr>
<td>2</td>
<td>45.51</td>
<td>4.05</td>
<td>7.83</td>
<td>0.60</td>
</tr>
<tr>
<td>3</td>
<td>45.59</td>
<td>4.16</td>
<td>7.70</td>
<td>0.62</td>
</tr>
<tr>
<td>4</td>
<td>45.06</td>
<td>4.11</td>
<td>7.49</td>
<td>0.61</td>
</tr>
<tr>
<td>6</td>
<td>45.15</td>
<td>3.79</td>
<td>6.90</td>
<td>0.58</td>
</tr>
<tr>
<td>8</td>
<td>46.66</td>
<td>3.75</td>
<td>6.08</td>
<td>0.59</td>
</tr>
</tbody>
</table>

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