Explicating Sediment Sources of the Catchment Upstream of the Miyun Reservoir in Beijing, China

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Research Article

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Explicating sediment sources of the catchment upstream of the Miyun Reservoir in Beijing, China

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Abstract

As the only water drinking resource in Beijing, the Miyun Reservoir is still suffered over ten thousand tons of sediment input from its upper catchment. Explicating sediment sources of the catchment upstream of the reservoir is urgently required to further implement soil conservation measures. In this paper, the Revised Universal Soil Loss Equation (RUSLE) and Sediment Delivery (SEDD) models were combined to explicate the major sediment source of the catchment through exploring the spatial distributions of soil erosion and sediment delivery as well as their relations with land use and topography, and sediment source areas were then identified. The catchment average soil erosion intensity (SEI) of 4.08 t ha⁻¹ yr⁻¹ was two times the soil loss tolerance (T=2.00 t ha⁻¹ yr⁻¹) of the study region. The values of cell sediment delivery ratio (SDR) showed a network distribution pattern, ranging from zero to unit, with an average of 1.65%. Cell specific sediment yield (SSY) presented a similar spatial
pattern to SDR, ranging from 0 to 902 t ha\(^{-1}\) yr\(^{-1}\), with an average of 0.04 t ha\(^{-1}\) yr\(^{-1}\). Bare land suffered the highest SEI of 39.01 t ha\(^{-1}\) yr\(^{-1}\), followed by shrub land and orchard field. Nearly 70% of the sediment came from grass land. Farmland was the second sediment contributor. Grass land and farmland are the two major sediment source areas. Soil conservation practices should be further implemented on these lands, especially on the 3-5° slopes with elevations less than 500 m a.s.l.

**Keywords** RUSLE• SEDD• soil erosion• sediment delivery• Beijing hilly region

**Introduction**

Water erosion can induce both on-site and off-site environmental problems (Wilkinson et al. 2009; Modes et al. 2020). Water erosion destroys on-site soil structure, lowers soil nutrient, and degrades land. The eroded sediment can induce off-site reservoir or river sedimentation and fresh water pollution (Walling et al. 1999; Rickson 2014; Vercruysse et al. 2017; Zhao et al. 2020). Exploration of the spatial distributions of soil erosion and sediment delivery should be done before soil conservation measures are further implemented in a targeted region.

In northern China, water issue such as water shortage and water pollution has been paid attention to in recent years because it has resulted in serious problem of water supply (Zhou and Wu 2008; Tang et al. 2011; Liu and Yu 2018). For example, due to severe water pollution and heavy sediment load, the Guanting Reservoir has been excluded as a source of drinking water for Beijing, the capital of China. Currently, Miyun Reservoir has become the only source of drinking water for the
people in Beijing. Thus, water protection of the Miyun Reservoir has received great
attention by local government, and soil conservation measures have widely been
implemented since the 1980s in the catchment above the reservoir (Li and Li 2008).
However, in recent years, mean annual sediment input from the catchment upstream
to the reservoir still reaches ten thousand tons. Therefore, it is urgently required to
explicate the sediment source.

In recent years, some studies which are related to sediment have been made in
the catchment above the Miyun Reservoir. For example, using the Revised Universal
Loss Equation (RUSLE), Feng et al. (2019) studied the impact of land use change on
soil erosion in the catchment upstream of the Miyun Reservoir, but it didn’t consider
sediment delivery in the catchment. Zhou and Wu (2008) explored the variations of
sediment deliver ratio (SDR) using the RUSLE and sediment yield (SY). Tang et al.
(2011) obtained the variations of runoff, sediment concentration, and total nitrogen
and total phosphorous at Xiahui and Zhangjiafen hydrological stations, based on a
non-point source pollution model. Regrettably, only catchment lumped sediment
delivery was considered, without considering its spatial distribution characteristics.
This impedes the identification of sediment source and future land use management in
the catchment.

Soil erosion modeling is an efficient and fast way to estimate soil erosion and
sediment delivery in a catchment (Fang and Sun 2017; Zerihun et al. 2018). In recent
decades, many models have been developed (Pandey et al. 2016). However, due to
limited data availability and simplicity, the RUSLE model is the most widely used one
all over the world to assess spatially distributed pattern of water erosion, particularly in a large catchment (Batista et al. 2017).

However, the RUSLE model does not consider sediment deposition, providing no information of sediment delivery within a catchment (Ranzi et al. 2012; Pandey et al. 2016). In fact, only part of the eroded sediment can be moved out of a catchment. The Sediment Delivery Distributed (SEDD) model was introduced to simulate catchment sediment delivery ratio (SDR) (Di Stefano et al. 2007). The theoretical approach followed by SEDD model requires a limited input data to estimate sediment delivery (Fu et al. 2006; Guo et al. 2019). The combination of RUSLE and SEDD models can thus provide a good approach to explicate the spatially distributed soil erosion and sediment delivery, especially in regions with limited data availability.

In the current study, the RUSLE and SEDD models were applied to explicate the sediment source through identifying the spatial distributions of water erosion and sediment delivery in the catchment upstream of the Miyun Reservoir, and to quantify the contributions of different land use types to the total catchment SY, and then priority regions were given for future implementation of soil conservation practices in the catchment.

Materials and methods

Study area description

The catchment upstream of the Miyun Reservoir is located in the northeast of Beijing city. Chaohe River and Baihe River are the two major tributaries that drain into the reservoir (Fig. 1). The catchment covers an area of 15331 km², with elevation ranging
from 65 to 2300 m a.s.l. Steep slope characterizes the study area, with a mean slope gradient of 34%. The areas with slope gradients above 26.8% and 46.6% occupy around 26% and 56% of the total, respectively.

**Fig. 1 is about here**

The region has a warm and continental monsoon climate. The mean annual precipitation is around 490 mm, 80% of which falls in summer period. The major soils are Calcic Luvisols, Calcaric Cambisols, Haplic Luvisols, and Haplic Chernozems, with areas occupying 27.6%, 25.1%, 20.3%, and 7.2% of the total, respectively.

The main land use types are forest and grass, occupying 63.3% and 22.3% of the total area respectively (Fig. 1). Forest, shrub, and grass are mainly distributed in high-elevation and steep areas. Farmland occupies around 10%, and is mainly distributed in gentle slope areas along the rivers (Fig. 2).

**Fig. 2 is about here**

Since the 1980s, more and more lands have been widely implemented with soil conservation measures (Li and Li 2008), including terrace, strip ridging, fish-scale pit which are mainly implemented in farmland and orchard field (Fig. 3cd). Compared to the years before 2000, the catchment SY in recent years is much lower (Li and Li, 2008). However, there is still over ten thousand tons of sediment entering the reservoir per year. For example, the mean annual SY in 2006-2016 at Xiahui station, the outlet of the Chaohu River, was $0.127 \times 10^4$ t, and that at the Zhangjiafen station, the outlet of the Baihe River, was $1.154 \times 10^4$ t (Table 1; Fig. 1). The total annual SY
entering the reservoir reached $1.284 \times 10^4$ t.

**Fig. 3 is about here**

**Data sources**

The RUSLE was used to estimate water erosion. To run this model, datasets including a Digital Elevation Model (DEM), the land use map in 2015, precipitation amount, land use management and soil conservation measures were obtained from different sources.

The DEM was downloaded from Shuttle Radar Topography Mission (SRTM) website. After projected with WGS 1984 N52, the resolution in the study area was 27 m.

The land use data in 2015 was downloaded from the website (http://data.ess.tsinghua.edu.cn/fromglc2017v1.html) by the research team of Gong Peng in Tsinghua University. The data has a 24.5 m resolution in the study area. This high-resolution data can well distinguish different land use types. The data accuracy has been verified by Gong et al. (2020).

The daily precipitation data in 2006-2016 at the 50 meteorological stations in the catchment were acquired from the National Climate Centre of Chinese Meteorological Administration (http://data.cma.cn/) and the Annual Hydrological Report of the People’s Republic of China.

The Harmonized World Soil Database (HWSD) Version 1.2 was obtained from Food and Agriculture Organization of the United Nations (FAO-UN; http://www.fao.org). Soil properties including sand, clay and silt, depth of soil,
organic carbon are available from the HWSD.

In the current study, due to the high-resolution land use data, all the data mentioned above were resampled using the nearest neighborhood method to a 25-m resolution.

During 2006-2016, daily sediment concentration and water level were monitored at eight hydrologic stations (Fig. 1; Table 1). Water discharge (Q) was obtained by using previously established Q-water level curve. Daily SY were then obtained by multiplying sediment concentration and Q (Fang 2019). Annual SY were summed by the daily SY (Table 1). The measured data has been checked and printed in the Annual Hydrological Report: Hydrological Data of Haihe River Basin.

Table 1 is about here

Methods

Field campaigns

In October and December 2019, two field campaigns were carried out. In October, runoff plots in Shixia subcatchment were investigated (Fig. 1b). The runoff plots were 10-m long with different slope gradients and land use types, some of which have been implemented with soil conservation measures (Table 2). After each rainfall, sediment and runoff collected by containers at the lower end of the plots are measured. Annual SY was obtained through summing the event-based SY occurred in a year. In the current study, annual SYs in 2014-2018 from nine runoff plots were used to verify the estimated results by the RUSLE model. The second field campaign in December was to check the accuracy of land use reclassification from Gong et al. (2020) for Beijing
hilly regions.

Table 2 is about here

RUSLE description

In the current study, the RUSLE modeling approach was used to estimate water erosion, which is calculated as the product of six factors:

$$E = R \times K \times LS \times C \times P$$  \hspace{1cm} (1)$$

where $E$ is the soil erosion intensity (SEI; t ha$^{-1}$ yr$^{-1}$), $R$ is the rainfall-runoff erosivity factor (MJ mm ha$^{-1}$ h$^{-1}$), $K$ is the soil erodibility factor (t ha$^{-1}$ MJ$^{-1}$ mm$^{-1}$), $LS$ is a combination of slope length $L$ and slope gradient $S$ factor (-), $C$ is the crop/cover management factor (-), and $P$ is the soil conservation factor (-).

$R$ factor

The method to estimate $R$ factor has been significantly improved over that in the original USLE approach. Except for the method proposed by Wischmeier and Smith (1978), alternative methods have widely been used to estimate $R$-factor value by using different time resolution data (Jiao et al. 2009; Lee et al. 2011). In the current study, the daily precipitation data in 1980-2016 was used to estimate $R$-factor values, using the method proposed by Zhang et al. (2003):

$$R_i = a \sum_{j=1}^{k} (D_j)^b$$  \hspace{1cm} (2)$$

Where $R_i$ is the half-month $R$-factor (MJ mm ha$^{-1}$ h$^{-1}$ yr$^{-1}$), and $D_j$ is the erosive rainfall day $j$. $D_j$ is equal to actual rainfall when it is greater than 12 mm. Otherwise it equal to zero. Here, $a$ and $b$ are empirical parameters. Detailed description was given by Fang and Sun (2017). A Co-Kriging interpolation was used to derive an $R$-factor
value map in ArcGIS 10.5 software. The mean annual R value in 2006-2016 ranged from 1222 to 4749 MJ mm ha\(^{-1}\) h\(^{-1}\) yr\(^{-1}\), with an average of 2802 MJ mm ha\(^{-1}\) h\(^{-1}\) yr\(^{-1}\) in the study catchment (Fig. 4a).

**Fig. 4 is about here**

### K factor

The K factor reflects soil erodibility as affected by intrinsic soil properties. In the current study, soil texture and soil organic carbon content on the top of 30 cm soil layer were extracted from the HWSD. The values of K factor were calculated using the EPIC approach which has been verified in the study area (Liu et al. 2010):

\[
K = 0.2 + 0.3e^{-0.0256SAN[1-SIL/100]} \times \left(\frac{SIL}{CLA+SIL}\right)^{0.3} \times \left[1 - \frac{0.25SC}{SC + e^{(3.72-2.95SC)}}\right]
\]

(3)

where \(SAN\) is the sand content (%), \(SIL\) is the silt content (%), \(CLA\) is the clay content (%), \(SC\) is the soil organic carbon content (%) and \(SN = 1-SAN/100\). A soil erodibility map was thus obtained, with K-factor values ranging from 0 to 0.064 t ha h MJ\(^{-1}\) mm\(^{-1}\) ha\(^{-1}\) in the study catchment (Fig. 4b).

### LS factors

The L and S factors represent the effect of topography on water erosion. A 2D approach was used to calculate L factor using the method proposed by Desmet and Govers (1996). The formula by McCool et al. (1989) was used to calculate S factor.

\[
L_{ij} = \frac{(A_{ij}+D^2)^{m+1} - A_{ij}^{m+1}}{b^{m+2}x_{ij}^{m+2}2.13^m}
\]

(4)

\[
x_{i,j} = \sin\alpha_{i,j} + \cos\alpha_{i,j}
\]

(5)

\[
m = \frac{\beta}{(1+\beta)}
\]

(6)
\[ \beta = \frac{(\sin\theta/0.0896)}{[3+(\sin\theta)^{0.8}]+0.56]} \]  

(7)

\[ S = \begin{cases} 
10.8\sin\theta + 0.03, & \theta < 9\% \\
16.8\sin\theta - 0.5, & \theta \geq 9\% 
\end{cases} \]  

(8)

where \( L_{i,j} \) is the slope length factor of the grid cell with coordinates \( i \) and \( j \), \( A_{i,j} \) is the contribution area at the inlet of a pixel (m\(^2\)), \( D \) is the grid cell size (m); \( \alpha_{i,j} \) is the slope aspect direction for a pixel; \( m \) is slope length exponent, \( \beta \) is empirical factor (-), and \( \theta \) is the slope angle. The calculated values of LS factor varied from 0.03 to 196.17, with an average of 5.01. Higher LS values occurred in mountainous regions, and lower values appeared along the valleys (Fig. 4c).

**C factor**

The C factor represents the impact of cropping and management practices on water erosion. In the study area, C-factor values for the land use types were obtained from the published literatures (Bi et al. 2006; Fu et al. 2006; Liu et al. 2010; Fang and Sun 2017; Zerihun et al. 2018; Devátý, et al. 2019; Jazouli et al. 2019). The largest C value was assigned to farmland, followed by orchard and wetland C values of 0.36 and 0.18, respectively (Table 3). The lowest C value of 0.001 was assigned to the forest land (Fig. 4d).

**Table 3 is about here**

**P factor**

Because extensive terrace and fit-scale practices have been implemented on farmland and in orchard field, an average value of P factor was set to 0.01 for the farmland, and a value 0.69 was given to the orchard field. The P values of other land use types were set to one (Table 3). The P map was illustrated in Fig. 4e.
SEDD description and calibration

The SEDD model was used to estimate cell SDR$_i$:

\[ SDR_i = e^{-\beta t_i} \]  

(9)

\[ t_i = \sum_{i=1}^{N_p} \frac{l_i}{v_i} \]  

(10)

where $\beta$ is a catchment-specific parameter, and $t_i$ is travel time of the eroded soils from the i cell to the nearest stream. It was calculated with the D8 distance to the channels using the TauDEM 5.3.7 module in ArcGIS software (Tarboton 2014). $N_p$ is the number of cells along a flow path to the nearest stream, and $v_i$ is the flow velocity passing a cell, which can be obtained using the following equation:

\[ v_j = k \sqrt{s_j} \]  

(11)

where $s_j$ is a cell’s slope in gradient (m m$^{-1}$), and $k$ is the surface roughness coefficient for a cell, and is expressed by sediment water velocity passing a type of land use (m s$^{-1}$). In the current study, $k$ values of different land use types were from published papers (Table 4). To ensure the proper use of Eq. (10), a minimum cell slope was set to 0.3%, as proposed by Fu et al. (2006).

Table 4 is about here

The parameter $\beta$ depends primarily on catchment geomorphology, and can be calculated with various candidates. A sensitive analysis is usually used to obtain an appropriate $\beta$ value. For example, Yang et al. (2012) estimated a $\beta$ value by changing its values from 4 to 5 with an increment of 0.1. Jain and Kothyari (2000) used this method to estimate $\beta$. An inverse modeling approach was also used (e.g., Fernandez et al. 2003; Stefano and Ferro 2007) to estimate $\beta$ when a mean SDR of a
catchment (SDRw) is known by field data or through developed relationships between SDRw and some catchment variables (e.g., Ferro and Porto 2000; Porto et al. 2011).

The catchment SY at Yunzhou hydrological station in 2006-2016 was zero because all the sediments were trapped by the Yunzhou reservoir. Similarly, zero SY also occurred at Baihebao hydrological station due to reservoir interception (Fig. 1). Therefore, only the SYs from other six hydrological stations in Table 1 were used to estimate β values. Because SY was zero at Yunzhou hydrological station, its controlled catchment area was deducted from that controlled by Xiabao hydrological station when the SEDD model parameters were calibrated. Similar treatment was also done when the SY at Zhanjiafen hydrological station was used to calibrate the model (Table 1).

The calibration procedure was similar to the methods by Fu et al. (2006) and Batista et al. (2017). A series of β values were tested for each catchment, and the estimated SYs were compared with the measured ones. The best fit value of β was obtained when the lowest error occurred. For example, the β values ranging from 0.05 to 4.50 were tested with an increment of 0.01 for Gubeikou catchment. Ultimately, the values of β for the six subcatchments controlled by Xiabao, Sandaoying, Zhangjiafen, Dage, Gubeikou, and Xiahui hydrological stations were obtained (Table 5).

**Table 5 is about here**

The spatial distributed cell SDR, of the catchments was obtained using Eq.(9), and then cell specific sediment yield (SSY,) was calculated based on the RUSLE
model:

\[
SSY_i = E_i \ast SDR_i \tag{13}
\]

where \(E_i\) is the SEI, and the SY of a given catchment was obtained by multiplying the mean \(SSY_i\) of the catchment and its area (km\(^2\)).

Indexes of topography and geomorphology

Because the \(\beta\) parameter depends mainly on morphologic data (Ferro and Minacapilli, 1995; Ferro et al. 2003), 12 indexes of topography and geomorphology were extracted from the DEM data for the six subcatchments (Table 1). These indexes include catchment area (\(A\)), catchment length (\(CL\)), relief difference (\(RD\)), the ratio of relief difference to catchment length (\(RD/CL\)), RUSLE-LS, the mean slope gradient of the river networks (\(MSR\)), the total river length (\(TRL\)), stream power index (\(SPI\)), drainage density (\(DD\)), plan curvature (\(PC\)), convergence index (\(CI\)), and topographic wetness index (\(TWI\)). Ferro (1997) concluded that some properties describing the geomorphology and the river networks greatly affected sediment transport efficiency. These indexes were then used to estimate a \(\beta\) value for the study catchment (Table 5).

Sediment trap efficiencies of the reservoirs

There are multiple methods to estimate a reservoir’s sediment trap efficiency (STE). In the study catchment above the Miyiun Reservoir, there are two large reservoirs named Yunzhou and Baihebao which are located on the Baihe River (Fig. 1). In 2006-2016, the SYs were zero at the Yunzhou and Baihebao hydrological stations which are located at the outlets of the reservoirs, implying that their STEs were 100%.
There are also many smaller reservoirs or ponds in the catchment (Li, 2007), however, their STEs were not obtained due to unavailable data in the current study.

**Results**

**Soil erosion**

The mean annual SEI of the catchment upstream of the Miyun Reservoir ranged from 0 to 902 t ha\(^{-1}\) yr\(^{-1}\), with an average of 4.08 t ha\(^{-1}\) yr\(^{-1}\) (Fig. 5). It was over two times the soil loss tolerance (T=2.00 t ha\(^{-1}\) yr\(^{-1}\)) in the study area (Hua et al. 2005). Around 62% of the cells had SEI less than one T. The area percentages of the cell SEIs with 2-5, 5-10, 10-15, 15-25, and 25-50 t ha\(^{-1}\) yr\(^{-1}\) were around 6.15%, 8.46%, 7.13%, 9.27%, and 6.3% respectively. The area percentage with SEI higher than 50 t ha\(^{-1}\) yr\(^{-1}\) was less than 1.0%.

Soil loss widely occurred in the catchment, and varied greatly. Higher SEI mainly appeared in the areas along the channels (Fig. 5). Considering the drainage area (15331 km\(^2\)) of the catchment, annual total soil loss reached 6,255,048 tons.

**Fig. 5 is about here**

**Calibrated \(\beta\)**

The calibration using the SYs from the 6 subcatchments (i.e., catchments controlled by Dage, Gubeikou, Xiahui, Sandaoying, Xiabao, and Zhangjiafen hydrological stations) yielded different \(\beta\) values, ranging from 0.04 in Dage subcatchment to 4.00 in Xiahui subcatchment (Fig. 1). Pearson correlation matrix showed that these \(\beta\) values were significantly correlated with A, CL, FD, and SPI at the 0.01 significance level, and FD/CL, PC at the 0.05 significance level (Table 6). The \(\beta\) values were
exponentially correlated with FD/CL and CI indexes, and linearly with other indexes.

After exponentially conversion of these two indexes, standardization of all the indexes, a stepwise linear regression was established with the F probability with entry of 0.05 and removal of 0.1, yielding a regression equation:

$$\beta = 0.961\text{CL}^* R^2 = 0.924$$  \hspace{1cm} (14)

where CL* is the standardized CL. According to this equation, a $\beta$ value of 1.73 for the catchment upstream of the Miyun Reservoir was obtained, considering a standardized CL* value of 1.797 for the whole catchment.

Table 6 is about here

**SDR and SSY**

A spatially distributed map of SDR$_i$ in the catchment upstream of the Miyun Reservoir was obtained using Eq. (9) with the estimated $\beta$ value of 1.73 (Fig. 6a). The values of cell SDR$_i$ ranged from 0 to 100%, with an average of 1.65%, and a standard deviation of 12.69%. Around 98% cells had an SDR$_i$ less than unit. Spatially, the SDR$_i$ showed a network distribution pattern. The farther away from the river networks, the smaller the SDR$_i$ values were.

The mean SSY$_i$ of the catchment ranged from zero to 902 t ha$^{-1}$ yr$^{-1}$, with an average of 0.04 t ha$^{-1}$ yr$^{-1}$ (Fig. 6b). The distance to streams greatly influenced SSY$_i$. The spatial distribution pattern of the cell SSY$_i$ was quite similar to that of the SDR$_i$, resulting from significant modification of SEI$_i$ by SDR$_i$. Around 68% of the cells had zero value, indicating that most of the eroded sediment cannot reach channels. The cells with 0-2 t ha$^{-1}$ yr$^{-1}$ occupied 30% of the total. The total annual SY of the
catchment was $6.90 \times 10^4$ t.

**Fig. 6 is about here**

**Discussion**

**Model performance**

This study uses RUSLE and SEDD models to estimate soil erosion and sediment delivery in the catchment upstream of the Miyun Reservoir. Therefore, their performance should be verified. In the study area, soil erosion has been studied using the RUSLE model (Zhou and Wu 2008; Feng et al. 2019), tracer method (Hua et al. 2005), and runoff plots (Table 7). In the current study, the estimated SEIs were 1.66 and 13.36 t ha$^{-1}$ yr$^{-1}$ on forest and grass lands. Such values are in agreement with the counterparts by Feng et al. (2019), which are 2.01 and 1.90 t ha$^{-1}$ yr$^{-1}$ on forest and grass lands, respectively. In contrast, the estimated SEI on the forest land was lower than that (i.e., 26.36 t ha$^{-1}$ yr$^{-1}$) by Hua et al. (2005). However, the estimated SEI of 20.84 t ha$^{-1}$ yr$^{-1}$ on shrub land in the current study coincided well with that (i.e.,17.30 t ha$^{-1}$ yr$^{-1}$) by Hua et al. (2005).

In respect of SEI on farmland, the estimated SEI of 6.15 t ha$^{-1}$ yr$^{-1}$ is much higher than that (i.e., 0.10 t ha$^{-1}$ yr$^{-1}$) on runoff plot. Similarly, the estimated SEIs on other types of lands are also higher than the counterparts on the runoff plots (Table 2). This could be due to lower slope length and slope gradient of the plots. This hypothesis can to some extent be verified that the SEI on the 14.4° runoff plot with contour cultivation is much higher than the estimated one in the current study.

Factors influencing water erosion are multiple, and methods used also greatly
influence the results. Thus, differences between our results and others are acceptable (Fang and Sun 2017).

The simulated SYs for the six subcatchments were compared to the measured ones in Table 1. As expected, the SSYs in smaller subcatchments (i.e., SY at Dage, Xiabao, and Sanyimiao) were underestimated, and verse visa (Fig. 7). However, the Adjusted $R^2$ of the fitting line reaches 0.64, resulting from the compromise of parameter calibration for different catchments.

**Fig. 7 is about here**

**Impact of land use**

The distribution of soil loss is greatly influenced by land use types (e.g., Ranzi et al. 2012; Naqvi et al. 2019). The distribution pattern of SEI was quite similar to that of the grassland because the grassland was widely distributed in the catchments with higher SEI of 13.36 t ha$^{-1}$ yr$^{-1}$. As a result, the SY from grass land contributed nearly 70% to the total. Although farmland was widely implemented with soil conservation measures, it occupied only 3.95% of the study area. The SY from the farmland occupied nearly 17% of the total, which was the second sediment contributor to the catchment. In contrast, forest area occupied near 64% of the total area, whereas its SY contribution to the total was less than 7%, resulting from smaller SEI (i.e., 1.66 t ha$^{-1}$ yr$^{-1}$) and SDR (i.e., 0.72%). In the study area, bare land suffered the highest SEI (i.e., 39.1 t ha$^{-1}$ yr$^{-1}$) and higher SDR (Table 7). This result coincided with published studies. For example, in the Isóbena catchment of southern central Pyrenees, most sediments came from the
bare land although its area percentage was less than 1% (López-Tarazón et al. 2009). The highest SEI was also observed in the upper Grande River catchment, Brazil (Batista et al. 2017). Therefore, bare land should be the priority area for future soil loss control. Orchard land also had much higher SEI (i.e., 17.73 t ha\(^{-1}\) yr\(^{-1}\)) with the largest SDR. However, because its area percentage was much less, its contribution to the total SY only occupied 0.02%. This type of land should also be paid attention to because soil loss from orchard field could lead to severe water pollution in the study area (Liu et al. 2003).

Table 7 is about here

Impact of topography

Both SEI and sediment delivery were greatly influenced by topography. Steeper slopes usually had higher values of LS factor (Vijith et al. 2018), resulting in higher SEI (Fig. 8ab). However, a threshold value of SSY occurred on the 3-5 degree slopes. On the gentle slopes, sediment does not easily enter the steams. However, sediment flow on steeper slopes usually requires a long distance to reach streams, resulting in a less SSY. Their interaction can thus produce a threshold value of SSY with increasing slope gradients.

Fig. 8 is about here

With respect to the impact of elevation on soil erosion and sediment delivery, both SEI and SSY presented decreasing trends with the largest values occurred in the 200-300 m a.s.l regions (Fig. 8). The RUSLE-derived soil erosion map apparently indicated higher SEI in this elevation range (Fig. 5). This could result from extensive
land reclamation in lower elevation areas in recent years (Pang et al. 2010; Feng et al. 2019).

Noticeably, forest, grass, and shrub lands were mainly distributed in in the steep areas with higher elevations (Fig. 2), where the rates of soil loss were lower on the forest and shrub lands, while higher SEI on the grass land (Table 6). The bare land which had the largest SEI is mainly distributed in the areas above 1000 m a.s.l. Soil loss control for these two types of lands also should be done.

**Uncertainty analyses**

The $\beta$ parameter is a major source of uncertainty in the SEDD model (Batista et al. 2017). The published $\beta$ values differed greatly in literature, varying from 0.2 h$^{-1}$ (Yan et al. 2018), 1.0 h$^{-1}$ (Fu et al. 2006), 3.0 h$^{-1}$ (Batista et al. 2017), to 4.6 h$^{-1}$ (Yang et al. 2012), respectively. The $\beta$ mainly depends on catchment geomorphology. It usually increases with increasing catchment area $A$ (Ferro and Minacapilli 1995; Batista et al. 2017). In the study area, it is not only positively correlated with $A$ at the significance of 0.01 level, but also correlated with other geomorphologic indexes (Table 6). This means larger catchment size doesn’t necessarily yield a large $\beta$ value.

The current study verifies this inference. The derived $\beta$ value of 1.73 from the stepwise regression equation Eq. (14) is smaller than those from Zhanjiafen, Gubeikou, and Xiahui catchments, and higher than those from other smaller catchments (Table 1). Batista et al. (2017) also pointed that although the $\beta$ generally increases with increasing catchment size, the relation may not be straight-forward.

The determined coefficient $R^2$ reached 0.64, indicating the estimated $\beta$ was
The combined use of RUSLE and SEDD models generated around $6.90 \times 10^4$ tons of sediment for the study catchment. This value is much higher than the summed SY ($1.281 \times 10^4$ t) monitored at the Zhanjiafen and Xiahui stations on the Baihe and Chaohe River outlets, respectively. The deviation could be explained by at least two aspects. In the study area, there were many dams or reservoirs, including the two largest ones named Yunzhou and Baihebao reservoirs on the Baihe River (Fig. 1). Much of the eroded sediment from catchment upstream is trapped by the reservoirs. For example, there was no sediment flowed out of the Yunzhou and Baihebao reservoirs in 2006-2016. This means that all the sediments from the upstream areas were trapped by these two reservoirs. The estimated annual SYs of $0.73 \times 10^4$ and $2.81 \times 10^4$ were trapped within the Yunzhou and Baihebao reservoirs, which occupied 11% and 41% of total SY. Many other reservoirs and dams exist in the study catchment (Li 2007), and a lot of sediment would be trapped in the reservoirs.

The study catchment has an area of 15,331 km$^2$ with zigzagged channels in the downstream areas (Fig. 1). As a result, more sediment is deposited on the flood plains (Bai et al. 2018; Zhang et al. 2019). However, sediment deposition is not considered in the SEDD, and the data of deposited sediment in channels are also unavailable. In the SEDD model, all the sediments from the upper slopes were directly routed out of the catchment, without considering sediment behavior in channels (Batista et al. 2017).

Therefore, the employment of the sediment data just from hydrological stations
could be biased, and more sediment information in channels should be explored and considered. Future version of SEDD that envelopes sediment suspension and deposition modules in channels could greatly improve its simulation accuracy.

Conclusions

Spatial distributions of water erosion and sediment delivery were explicated by using RUSLE and SEDD models for the catchment upstream of the Miyun Reservoir, and sediment sources areas were was recognized in the current study.

In the catchment, bare land suffered the highest SEI of 39.01 t ha\(^{-1}\) yr\(^{-1}\). Higher SEIs also occurred on the shrub land, orchard field, and grass land. Orchard field had the highest SDR of 10.35%, but its contribution of SY was less due to its less area percentage. The SY mainly came from grass land and farmland, occupying around 70% and 17% of the total, respectively. Soil conservation practices should focus on these lands to further control soil loss, especially those located in the regions with 3 to 5° slopes and/or elevations less than 500 m a.s.l.

Because no specific field data of sedimentation in the river networks, dams and/or reservoirs in the catchment, the estimated $\beta$ value could under- and over-estimate sediment delivery over the catchment. A model with sediment suspension and deposition modules in channels could better elucidate sediment delivery of the catchment when more robust field data are available. However, the combination of RUSLE and SEDD can still help explicate the major sediment source and guide future implementation of soil conservation measures in the Beijing hilly regions.
Acknowledgments

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Table 1 The catchment area, annual mean catchment sediment yield (SY) and area specific SY (SSY) in 2006-2016 controlled by the eight hydrological stations on the Chaohe and Baihe Rivers.

| Rivers | Station name | A km² | SY 10⁴ t yr⁻¹ | SSY t km⁻² yr⁻¹ |
|--------|--------------|-------|---------------|-----------------|
| Chaohe | Dage◆        | 1850  | 20.057        | 108.42          |
|        | Gubeikou◆    | 4701  | 1.906         | 4.05            |
|        | Xiahui◆      | 5340  | 0.127         | 0.24            |
| Baihe  | Yunzhou      | 1170  | 0.000         | 0.00            |
|        | Xibao◆       | 4015  | 4.632         | 11.54           |
|        | Baihebao     | 4040  | 0.000         | 0.00            |
|        | Sandaoying◆  | 1536  | 2.302         | 14.99           |
|        | Zhangjiafen◆ | 8506  | 1.154         | 1.36            |

Note: ◆ indicates the SY used to calibrate SEDD model.

Table 2 Land use types, slope gradients, implemented measures, and mean annual SEIs of different runoff plots in the Shixia subcatchment in 2014-2018.

| Runoff plot | Land use type       | Slope (°) | Measures                  | Mean annual SEI (t ha⁻¹ yr⁻¹) |
|-------------|---------------------|-----------|---------------------------|-------------------------------|
| 1           | Terrace (corn)      | 3.5       | Width: 4m                 | 0.10                          |
| 2           | Contour cultivation (corn) | 14.4 | -                         | 20.92                         |
| 3           | Farmland (corn)     | 16.5      | -                         | 27.31                         |
| 4           | Bare land           | 16.5      | -                         | 26.40                         |
| 5           | Chestnut            | 16.5      | Width: 3m, Coverage: 50%  | 1.37                          |
| 6           | Arbor               | 17.1      | Fish-scale pit; 80% coverage | 0.04                          |
| 7           | Shrub land          | 18.6      | Coverage: 50%             | 0.22                          |
| 8           | Grassland           | 19.0      | Coverage: 80%             | 0.04                          |
| 9           | Grassland           | 19.0      | Coverage: <30%            | 2.52                          |
Table 3 The values of RUSLE-C and -P factors used in the current study.

| Land use type          | C    | P    | Reference                                      |
|------------------------|------|------|-----------------------------------------------|
| Farmland               | 0.47 | 0.1  | Bi et al. 2006; Liu et al. 2010                |
| Forest                 | 0.001| 1.00 | Liu et al. 2010; Zerihun et al. 2018; Devátý, et al. 2019 |
| Orchard                | 0.23 | 0.69 | Bi et al. 2006; Liu et al. 2010                |
| Shrubland              | 0.029| 1.00 | Liu et al. 2010                                |
| Grassland              | 0.033| 1.00 | Liu et al. 2010                                |
| Marshland, wetland     | 0.18 | 1.00 | Fang and Sun 2017                              |
| Water                  | 0    | 1.00 | Fu et al. 2006; Fang and Sun 2017              |
| Impervious surface     | 0.003| 1.00 | Fu et al. 2006; Jazouli et al. 2019            |
| 8, Bare land           | 0.181| 1    | Fang and Sun 2017                              |

Note: All the studies in “reference” column were conducted in the NEC.

Table 4 The values of $k$ (m s$^{-1}$) in the SEDD model for different land use types (Sources: Ferro and Porto, 2000; Fernandez, et al. 2003; Yan et al. 2018; Batista et al. 2017)

| Land use type          | $k$ (m s$^{-1}$) |
|------------------------|------------------|
| Forest                 | 0.75             |
| Shrubland, and orchard | 0.75             |
| Grassland              | 2.13             |
| Residential land       | 5.14             |
| farmland               | 2.62             |
| Water                  | 4.91             |
Table 5. Extracted indexes of topography and geomorphology for the subcatchments controlled by the six hydrological stations in Table 1.

|          | Dage   | Gubeikou | Xiahui | Xiabao | Sandaoying | Zhangjiafen |
|----------|--------|----------|--------|--------|------------|-------------|
| $\beta$  | 0.04   | 3.82     | 4.00   | 0.34   | 0.21       | 3.55        |
| A (km$^2$) | 1857   | 4627     | 4800   | 2909   | 1536       | 4554        |
| CL (km)  | 59.74  | 131.32   | 141.53 | 79.38  | 85.57      | 118.80      |
| RD (km)  | 1575   | 1989     | 2008   | 1591   | 1768       | 2117        |
| RD/CL (-) | 26.36  | 15.15    | 14.19  | 20.04  | 20.66      | 17.82       |
| RUSLE-LS | 5.07   | 5.36     | 5.34   | 5.29   | 6.26       | 6.73        |
| MSR (m m$^{-1}$) | 0.043 | 0.039   | 0.039  | 0.041  | 0.05       | 0.05        |
| TRL (km) | 523.38 | 3440.24  | 3571.60| 2140.21| 1113.80    | 3247.18     |
| SPI      | 29647.55 | 73779.05 | 80125.58 | 34326.9 | 42240.08   | 101386.93   |
| DD (km km$^{-1}$) | 0.28   | 0.74     | 0.74   | 0.74   | 0.73       | 0.71        |
| PC ($\times 10^3$) | 0.18   | 0.22     | 0.22   | 0.19   | 0.20       | 0.25        |
| CI ($\times 10^3$) | -0.68 | -0.79   | -0.86  | -0.74  | -0.54      | -0.76       |
| TWI      | 6.49   | 6.46     | 6.47   | 6.52   | 6.32       | 6.23        |

Note: The abbreviation A, CL, RD, RD/CL, RUSLE-LS, MSR, TRL, SPI, DD, PC, CI, TWI represents catchment area, catchment length, relief difference, the ratio of relief difference to catchment length, RUSLE-LS, the mean slope gradient of river networks, total river length, stream power index, drainage density, plan curvature, convergence index, and topographic wetness index, respectively.
Table 6 Pearson correlation matrix between β and the 12 indexes of topography and morphology.

|       | β   | A   | CL  | RD  | RD/CL | RUSL E-LS | MSR  | TRL  | SPI  | DD   | PC   | CI   |
|-------|-----|-----|-----|-----|-------|-----------|------|------|------|------|------|------|
| A     | 0.960** |     |     |     |       |           |      |      |      |      |      |      |
| CL    | 0.961** | 0.909* |     |     |       |           |      |      |      |      |      |      |
| RD    | 0.923** | 0.827* | 0.902* |     |       |           |      |      |      |      |      |      |
| RD/CL | -0.862* | -0.853* | -0.956* | -0.796 |     |           |      |      |      |      |      |      |
| RUSLE-LS | 0.179 | 0.081 | 0.186 | 0.531 | -0.158 |           |      |      |      |      |      |      |
| MSR   | -0.269 | -0.381 | -0.277 | 0.112 | 0.316 | 0.877*    |      |      |      |      |      |      |
| TRL   | 0.934** | 0.973** | 0.940** | 0.833* | -0.939* | 0.153 | -0.336 |      |      |      |      |      |
| SPI   | 0.920** | 0.867* | 0.860* | 0.978** | -0.748 | 0.527 | 0.108 | 0.849* |      |      |      |      |
| DD    | 0.476 | 0.501 | 0.648 | 0.541 | -0.821* | 0.394 | 0.011 | 0.685 | 0.486 |      |      |      |
| PC    | -0.841* | 0.788 | 0.790 | 0.959** | -0.702 | 0.667 | 0.262 | 0.795 | 0.981** | 0.543 |      |      |
| CI    | -0.773 | 0.886 | -0.698 | -0.504 | 0.647 | 0.319 | 0.674 | -0.810 | -0.587 | -0.229 | -0.454 |      |
| TWI   | -0.219 | -0.085 | 0.195 | -0.568 | 0.113 | -0.981* | -0.880* | -0.124 | -0.588 | -0.266 | -0.680 | -0.315 |

* Significant at 0.05 level; ** significant at 0.01 level.
**Table 7** Soil erosion intensity (SEI), SDR, and SY at each land use type.

| Land use class      | SEI (t ha\(^{-1}\) yr\(^{-1}\)) | SDR (%) | SSY (t ha\(^{-1}\) yr\(^{-1}\)) | Area (km\(^2\)) | SY t yr\(^{-1}\) | SY % |
|---------------------|----------------------------------|---------|----------------------------------|------------------|-----------------|-----|
| 1, Farmland         | 6.14                             | 6.71    | 0.39                             | 629.50           | 24.660          | 16.86 |
| 2, Orchard          | 17.73                            | 10.35   | 2.02                             | 0.13             | 0.00            | 26   |
| 3, Forest           | 1.66                             | 0.72    | 0.01                             | 9207.74          | 57.83           | 9361 |
| 4, Grass land       | 13.36                            | 2.55    | 0.18                             | 5613.16          | 35.26           | 102,033 |
| 5, Shrubland        | 20.84                            | 1.19    | 0.16                             | 311.33           | 1.96            | 4,892 |
| 6, Water body/wetland | 2.08                           | 4.77    | 0.21                             | 86.83            | 0.55            | 1,789 |
| 7, Impervious surface | 2.42                          | 5.17    | 0.09                             | 33.50            | 0.21            | 316  |
| 8, Bare land        | 39.01                            | 4.35    | 0.82                             | 38.97            | 0.24            | 3,195 |


Figure captions:

Fig. 1 Maps showing (a) location of the catchment upstream of the Miyun Reservoir, (b) the distributions of hydrological stations, meteorological stations, Shixia subcatchment, reservoirs, and the elevation range, (c) slope gradient, and (d) land use types

Fig. 2 The mean slope gradients and elevations of different land use types distributed in the study catchment. Note: the numbers in the x-axis represent land use types in Table 7

Fig. 3 Pictures showing (a) runoff plot with bare soil, (b) forest, (c) terraced farmland, and (d) tree tray in the orchard field

Fig. 4 Spatial distributions of the values of RUSLE-R, -K, -LS, -C, and -P factors in the study catchment

Fig. 5 Spatial distribution of the estimated soil erosion intensity (SEI) in the study catchment

Fig. 6 Map showing the spatial distributions of the estimated SDR (a) and SSY (b).

Fig. 7 Comparison between the measured SSY with the simulated ones for the six subcatchments in Table 1

Fig. 8 Soil erosion intensity (SEI) and SSY (ac), and RUSLE-LS factor and flow length of the cells to the nearest channels with increasing slope gradients and elevations (bd)
Fig. 1
Fig. 2
Fig. 3
Fig. 4
Fig. 5
Simulated SSY ($10^{-2}$ t ha$^{-1}$ yr$^{-1}$)

- Xiabao
- Sandaoying
- Dage

$y = 5.40 + 0.02x$

N = 6, Adj. $R^2 = 0.64$

Fig. 7
Fig. 8
Maps showing (a) location of the catchment upstream of the Miyun Reservoir, (b) the distributions of hydrological stations, meteorological stations, Shixia subcatchment, reservoirs, and the elevation range, (c) slope gradient, and (d) land use types. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.
Figure 2

The mean slope gradients and elevations of different land use types distributed in the study catchment. Note: the numbers in the x-axis represent land use types in Table 7.
Figure 3

Pictures showing (a) runoff plot with bare soil, (b) forest, (c) terraced farmland, and (d) tree tray in the orchard field
Figure 4

Spatial distributions of the values of RUSLE-R, -K, -LS, -C, and -P factors in the study catchment. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.
Figure 5

Spatial distribution of the estimated soil erosion intensity (SEI) in the study catchment. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.
Map showing the spatial distributions of the estimated SDR (a) and SSY (b). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.
Figure 7

Comparison between the measured SSY with the simulated ones for the six subcatchments in Table 1
Figure 8

Soil erosion intensity (SEI) and SSY (ac), and RUSLE-LS factor and flow length of the cells to the nearest channels with increasing slope gradients and elevations (bd)