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Using WaTEM/SEDEM to Configure Catchment Soil Conservation Measures for the Black Soil Region, Northeastern China

Haiyan Fang [1,2]

[1] Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China; fanghy@igsnrr.ac.cn
[2] College of Resources and Environment, University of Chinese Academy of Sciences, Beijing 100049, China

Abstract: In recent years, to combat soil erosion, large-scale soil conservation measures have been implemented in the world. Evaluation of the integrated catchment management is urgently required. In the present study, soil erosion and sediment yield under 24 scenarios were predicted, based on the water and tillage erosion model and sediment delivery deposition model (WaTEM/SEDEM). The current catchment management was not ideal, with a catchment soil loss rate (SLR) of 599.88 t km^{-2} yr^{-1} and a sediment yield of 240.00 t km^{-2} yr^{-1}. The catchment management with contour tillage on <3° slopes, hedgerow planting on 3–5° slopes, terracing on 5–8° slopes, and forestation on >8° slopes with trenches along the forest and dams in gullies was the best catchment management to control soil loss, with catchment SLR that was less than the tolerable value of 200 t km^{-2} yr^{-1}. However, the SLR on the <3° slopes was still higher than the tolerable value. It is not enough to control soil loss by only implementing contour tillage measure on <3° slopes, and other measures should be further implemented on these slopes. In gullies, more measures should be implemented to prevent sediment flowing out of the catchments, in Northeastern China.

Keywords: soil erosion; soil conservation measure; spatial configuration; black soil region

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1. Introduction

Soil erosion severely degrades agricultural lands, through reducing soil depth, soil nutrients, and decreasing agricultural production [1–4]. Each year, around 36–75 billion top soil was lost in the world, resulting in severe nutrient loss [5], with an annual reduction in crop yields of 0.4–0.8% [6,7].

To combat soil erosion, soil conservation measures are widely used in the world, including contour tillage, terrace, hedgerow on slopes, ditch and dams in gullies, etc. The effects of the measures and their soil loss control efficiencies were well studied in China [8], Europe [9], Africa [10], Austria [11], and other regions in the world [12]. These studies evaluated the efficiencies of soil conservation measures separately. The combined efficiency of different measures in a catchment was also conducted using the changes in sediment yield or soil erosion models. For example, Qiu et al. [13] evaluated the impacts of different best-management practices on runoff, soil loss, and nutrient loss, using the SWAT model, and found that the implemented soil conservation measures decreased runoff discharge entering the Miyun Reservoir. Li [14] also found that the reduced runoff discharge was caused by the implemented soil conservation measures. Diyabalanage et al. [15] evaluated changes in soil erosion and sediment yield, as impacted by soil and water conservation measures in the central highlands of Sri Lanka, and found that the implemented soil conservation measures had greatly contributed to the reduction in catchment soil erosion. The conclusions, especially the combined implementation of different soil conservation measures in a catchment can greatly help policy makers to implement soil conservation measures. As we know, soil conservation measures are multiple, and therefore, the selection

of these measures and their combined implementation in a small catchment could affect their efficiencies in controlling soil erosion [16,17]. A reasonable combination of different soil conservation measures is crucially important to reduce soil erosion, and to improve crop production and living conditions [18].

The black soil region covers an area of 1.24 million km^2, and is one of the most important grain-producing areas in China [19]. Nevertheless, intense soil erosion has occurred, due to large-scale land reclamation in the 1950s, and the thickness of the A-horizon of the black soils has decreased from 60–70 cm since then to 20–30 cm at present [20,21]. In some places, the loess parent material has been exposed, greatly reducing soil productivity [22]. Since 2000, large scale soil conservation measures have been implemented in this region, including, for instance, contour tillage, terracing, hedgerow planting, and sediment retention dams [23,24]. For example, in Heilongjiang Province, the implemented soil conservation measures during 2016–2020 approached 21.1 thousand km^2 (http://www.slwr.gov.cn/, accessed on: 15 July 2021). The effects of most of these techniques have been analyzed using experimental plots [2] or model simulation [24]. However, their integrated impact at a catchment scale remains unclear, although this information is crucially important to better control soil loss.

In China, a small catchment is usually regarded as a basic unit to implement soil conservation measures [24]. Since the 1980s, the three defensing lines have been constructed in the major water erosion regions in China, such as on the Loess Plateau [25] and in the purple soil region [26]. In the black soil region, Sun et al. [27] also gave an integrated management strategy, through constructing three defensing lines to control soil loss in a catchment (Figure 1). Although these soil conservation strategies have been given in these regions, quantitative analysis on the catchment management was seldom reported. Is the conservation strategy effective to control soil loss? To evaluate this strategy and to find more suitably localized control measures in a catchment, it is vitally important to further control soil loss for the black soil region.

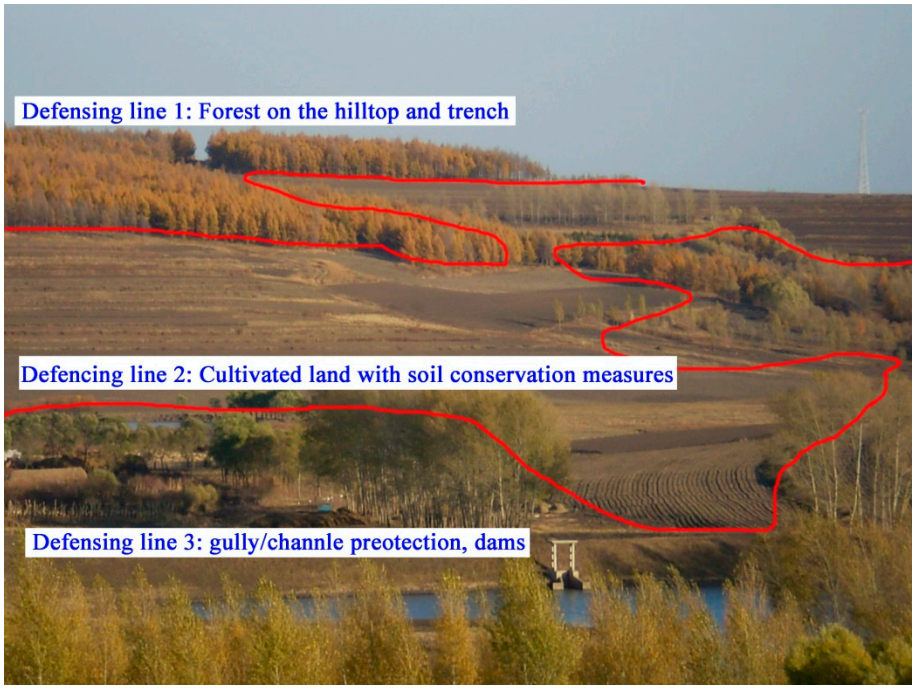

Figure 1. A picture showing the three defensing lines in Baiquan County, Northeastern China. The first defensing line is to plant trees and dig trenches at the lower edge of forest, the second defensing line is to control soil loss on the cultivated land with soil conservation measures, and the third line is to intercept sediment using dams in gullies and channels.

Soil erosion modeling is an efficient method to evaluate the effect of soil conservation measures [28]. Many soil erosion models, such as the water erosion predict project (WEPP), soil and water assessment tool (SWAT), and TeTIS, have been widely used to simulate water erosion [24,29]. Among the physically based models, the water and tillage erosion model and sediment delivery model (WaTEM/SEDEM) has similar data requirements as the revised universal loss equation (RUSLE), and can be validated with multiple data sources, such as sediment yield (SY) data at hydrological stations (e.g., Alatorre et al. [30]), sedimental data from ponds or reservoirs (e.g., van Rompaey et al. [31]), and soil erosion rates on slopes derived from the ^{137}Cs tracer [32]. Therefore, this model has been widely used in data scarcity regions in the world. In the black soil region, the effects of land use change, dam construction, and soil conservation measures on soil loss have also been evaluated using WaTEM/SEDEM [33,34]. However, the integrated effects of catchment management practices on soil loss were seldom found in the black soil region, Northeastern China.

The aims of the present study were to evaluate the effects of the three defensing lines management in a small catchment on soil loss, using different scenarios, pointing out the optimal conservation management, and giving some implications and suggestions for improvement of catchment management.

2. Materials and Method

2.1. Study Area

The Qixin catchment is located in the southeastern region of Baquan County, Heilongjiang Province (Figure 2). This catchment is controlled by the Qixin Reservoir, and has an area of 9.9 km^2. It belongs to one of the 25 reservoir catchments in Baiquan County (Figure 2b), which has been reported by Fang and Sun [34]. Long and gentle slopes characterize the topography. The elevation of the catchment ranges from 200 to 270 m. The climate is semi-humid and continental. The mean annual temperature is 1.28 °C and the mean annual precipitation is 475 mm [34].

The dominant soils are Mollisols and Phaeozems in FAO taxonomy. Silt clay loam characterizes the soil texture. The parent materials are quaternary lacustrine and fluvial sand beds or loess sediment.

Around 71% of the lands were cultivated, and bean and corn are the major crops. Forest and grass scatter the catchment, and a large patch of forest is located on the hilltop. To control soil loss, soil conservation measures have been implemented in this catchment. Up-downslope (UD) tillage is distributed on the slopes with gradients below 3°. Slopes with gradients between 3° and 5° are contour tilled. Slopes with gradients between 5° and 8° are implemented with terrace. The slopes with gradient above 8° are terrace or planted with trees.

2.2. WaTEM/SEDEM

Simulations were carried out using the spatially distributed WaTEM/SEDEM. It was developed based on the RUSLE, sediment transport capacity, and sediment routing module. It uses a multiple flow algorithm to calculate runoff pattern [35]. Sediment is routed along the runoff pattern and transferred downslope. The SYs from 25 reservoir catchments in Baiquan County had been used by Fang et al. [13] to calibrate and validate WaTEM/SEDEM (Figure 2b), and the high (i.e., 0.55) and low (i.e., 0.38) transport coefficient *Ktc* values were obtained.

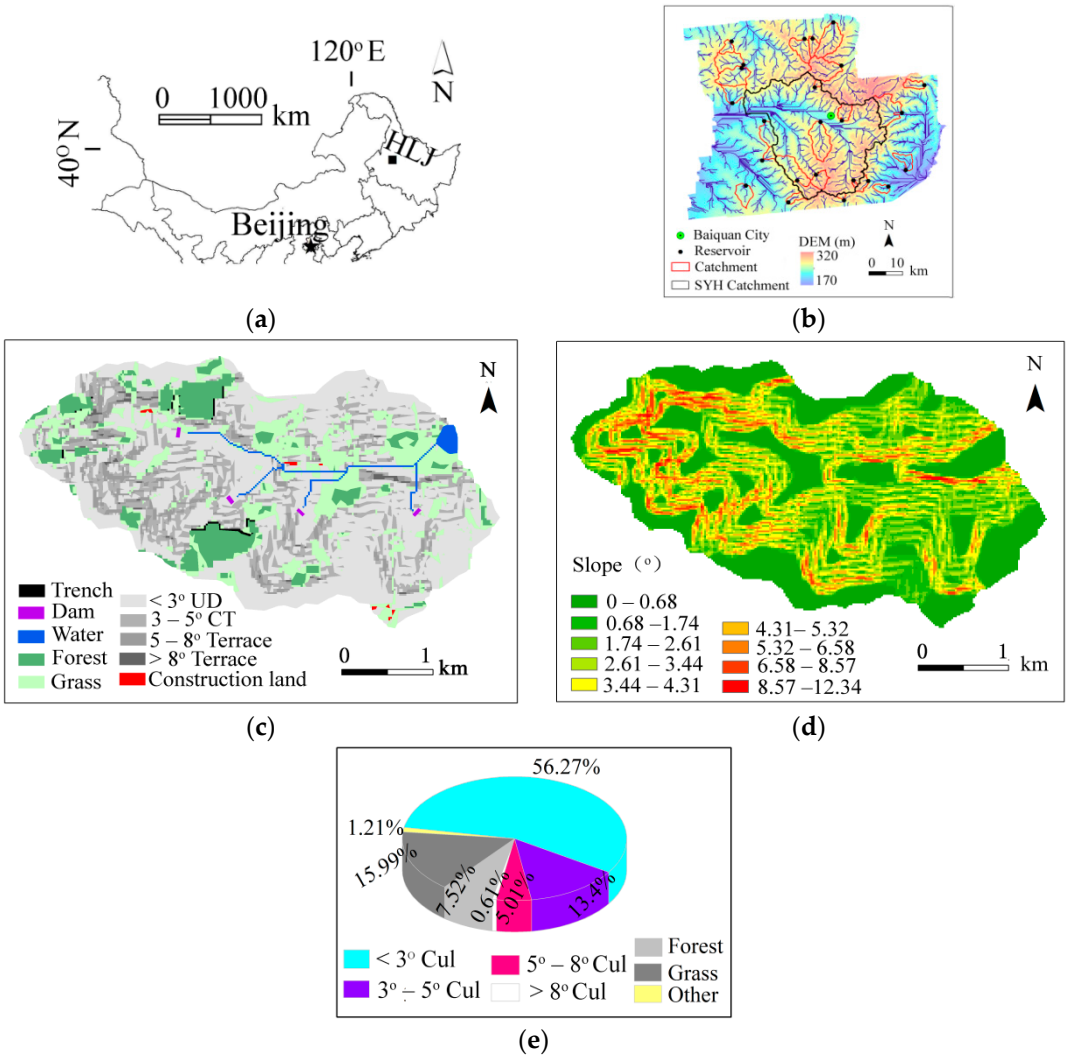

Figure 2. Location of the study catchment (**a**,**b**), land use type (**c**), catchment slope degree (**d**), and the percentages of land use types on different slope gradients (**e**). Note, (**c**) UD represents up-downslope cultivation, CT represents contour tillage; (**e**) Cul represents cultivated land, and HLJ represents Heilongjiang Province.

The WaTEM/SEDEM is a pixel-based model. First, soil erosion was predicted using the RUSLE, taking into account the two-dimensional slope length and slope gradient (LS) factor. The RUSLE has been used for soil loss prediction in the study area (e.g., Fang et al. [19], Haiyan et al. [13], Wei et al. [36], Zhang et al. [37], Wang et al. [38]). Therefore, the RUSLE parameters in our model were taken from these studies. Secondly, a transport capacity map is produced, which assumes that the capacity is proportional to concentrated flow erosion. Third, a runoff pattern is calculated with the digitized elevation model (DEM) that allows sediment to route downstream, considering the local transport capacity of each pixel.

2.3. Data Requirement

In order to run this model, several data layers are required, including a DEM, a land use map, a river network, a parcel map, a soil erodibility map, and a soil conservation practice map.

The DEM with 20 m was obtained through digitizing 1:50,000 topographic maps. It was used to extract river system and calculate a two-dimensional LS_{2D} factor for routing the sediment. The LS_{2D} factor uses the upslope unit contributing area instead of the upslope length to account for flow convergence [35].

The land use types of the catchment were extracted from a 10 m resolution land use map, which had a classification accuracy above 72% [39]. The reported values of RUSLE-C and *p* factor values were used in the study area (Table 1).

Table 1. The RUSLE-C and *p* values used in the present study were from [24].

Land Use Type	C	*p*
Water body	0	0
Residential areas	0.03	1
Forest land	0.004	1
Shrub land	0.04	1
Grassland	0.043	1
Terrace	0.2626	0.029
Contour	0.2626	0.352
Up-downslope tillage	0.2626	1

Note: $p = 1$ indicates soil conservation measures did not exist.

Soil types of the catchment were acquired from a 1:100,000 soil map, and the K-factor value of each soil type has been given by Wei et al. [36]. The rainfall erosivity R factor was calculated with daily rainfall data in the study region using the equation by Zhang et al. [40], as follows:

$$R_i = \alpha \sum_{j=1}^{n} (d_j)^{\beta} \quad (1)$$

$$\alpha = 21.586\beta^{-1.7891} \quad (2)$$

$$\beta = 0.8363 + \frac{18.177}{\overline{P_{d12}}} + \frac{24.455}{\overline{P_{y12}}} \quad (3)$$

where R_i is the half-month R-factor (MJ mm h^{-1} ha^{-1} yr^{-1}), and d_j is the erosive rainfall for day j in one half-month. d_j is equal to the actual rainfall when it is greater than 12 mm. Otherwise d_j is equal to zero. The n is the number of days in the half-month. $\overline{P_{d12}}$ and $\overline{P_{y12}}$ are the average daily and yearly rainfall amounts larger than 12 mm in value for each rainfall event.

Because there were no detailed measurements on sediment inflow and outflow data from the dams or trenches, their sediment trap efficiencies (STE) were obtained using the method given by Brown [41], as follows:

$$STE = 100 * \left(1 - \frac{1}{1 + 0.0021D\frac{Ca}{W}}\right) \quad (4)$$

where Ca (m^3) is the storage of the dams or trenches and W (m^2) is their controlled area. Values of D range from 0.046 to 1 with a mean of 0.1 depending on the texture of suspended sediment. In the present study, the mean D value was used due to no detailed data available.

2.4. Catchment Management Scenarios

In the study area, contour tillage (CT), hedgerow planting (HP), terrace (T_{er}) were mostly commonly used on slopes to control soil loss [13]. In order to prevent runoff from flowing downslope, some trenches were dug between hilltop forest and cultivated land, and dams were also constructed in gullies to trap sediment (Figure 2c). Based on the current conservation measures, in total 24 soil conservation scenarios in the catchment were supposed (Table 2), including the current management (i.e., baseline scenario 5). A brief explanation of each scenario is given in Table 2.

Table 2. Scenarios of soil conservation measures on slopes and gullies and simulation results for the Qixin catchment management.

Group		0–3°	3–5°	5–8°	>8°	SLR	SY	D_{dam}	SDR
1, no trenches and dams	S1	UD	CT	Ter	Fr	595.86	238.28	-	39.99
	S2	CT	CT	Ter	Fr	321.31	139.19	-	43.32
	S3	CT	HP	Ter	Fr	201.31	95.96	-	47.67
	S4	CT	HP	HP	Fr	219.70	101.41	-	46.16
2, no trenches and dams	S5	UD	CT	Ter	Ter	598.99	240.00	-	40.07
	S6	CT	CT	Ter	Ter	323.54	140.91	-	43.55
	S7	CT	HP	Ter	Ter	203.13	97.17	-	47.84
	S8	CT	HP	HP	Ter	216.87	101.01	-	46.58
3, with trenches	S9	UD	CT	Ter	Fr	584.55	237.88	90	40.69
	S10	CT	CT	Ter	Fr	315.66	138.99	49	44.03
	S11	CT	HP	Ter	Fr	197.47	95.76	30	48.49
	S12	CT	HP	HP	Fr	215.56	101.21	32	46.95
4, with trenches	S13	UD	CT	Ter	Ter	587.68	239.29	90	40.72
	S14	CT	CT	Ter	Ter	317.88	140.40	49	44.17
	S15	CT	HP	Ter	Ter	199.29	96.97	30	48.66
	S16	CT	HP	HP	Ter	212.83	100.81	31	47.37
5, with trenches and dams	S17	UD	CT	Ter	Fr	582.93	232.02	173	39.80
	S18	CT	CT	Ter	Fr	315.05	135.56	109	43.03
	S19	CT	HP	Ter	Fr	196.87	93.74	77	47.61
	S20	CT	HP	HP	Fr	215.05	98.89	81	45.98
6, with trenches and dams	S21	UD	CT	Ter	Ter	586.06	233.43	173	39.83
	S22	CT	CT	Ter	Ter	317.27	137.07	108	43.20
	S23	CT	HP	Ter	Ter	198.69	94.95	77	47.79
	S24	CT	HP	HP	Ter	212.32	98.59	80	46.43

Note: SLR represents soil loss rate (t km^{-2} yr^{-1}); SY presents sediment yield (t km^{-2} yr^{-1}); D_{dam} represents sediment amount deposited in dams and/or trenches; SDR represents sediment delivery ratio (%). UD represents up-downslope cultivation, HP represents hedgerow planting, CT represents contour tillage, Ter represents terracing, and Fr represents forest.

2.5. Soil Loss and Sediment Yield Control Efficiencies

In the present study, soil loss and sediment yield control efficiencies were estimated using the values of from baseline scenario, as follows:

$$CE = 100 \times \frac{X_0 - X_i}{X_0} \quad (5)$$

where CE represents annual soil loss or annual sediment yield control efficiency, X_0 represents annual soil loss or annual sediment yield under baseline scenario (i.e., scenario 5 in the present study), and X_i represents soil loss or sediment yield under different land use scenarios (i = 1, 2, 3, 4, 5, 6, . . . , 23, 24).

3. Results

3.1. Soil Erosion and Sediment Yield

The mean catchment SLRs varied greatly among different management scenarios. The visual inspect demonstrated that the SLRs under scenarios 1, 5, 9, 13, 17, and 21, with UD slopes, suffered the most intense soil erosion among each group (Figure 3), with SLRs ranging from 582.9 to 595.9 t km^{-2} yr^{-1} (Figure 4). When the slopes with gradients less than 3° were implemented with the CT measure, the SLRs decreased greatly, with values ranging from 315 to 323 t km^{-2} yr^{-1}. The SLRs decreased again under the scenarios of 4, 8, 12, 16, 20, and 24, and the scenarios of 3, 7, 11, 15, 19, and 23 produced the lowest SLRs, with values ranging from 196.9 to 203.1 t km^{-2} yr^{-1}.

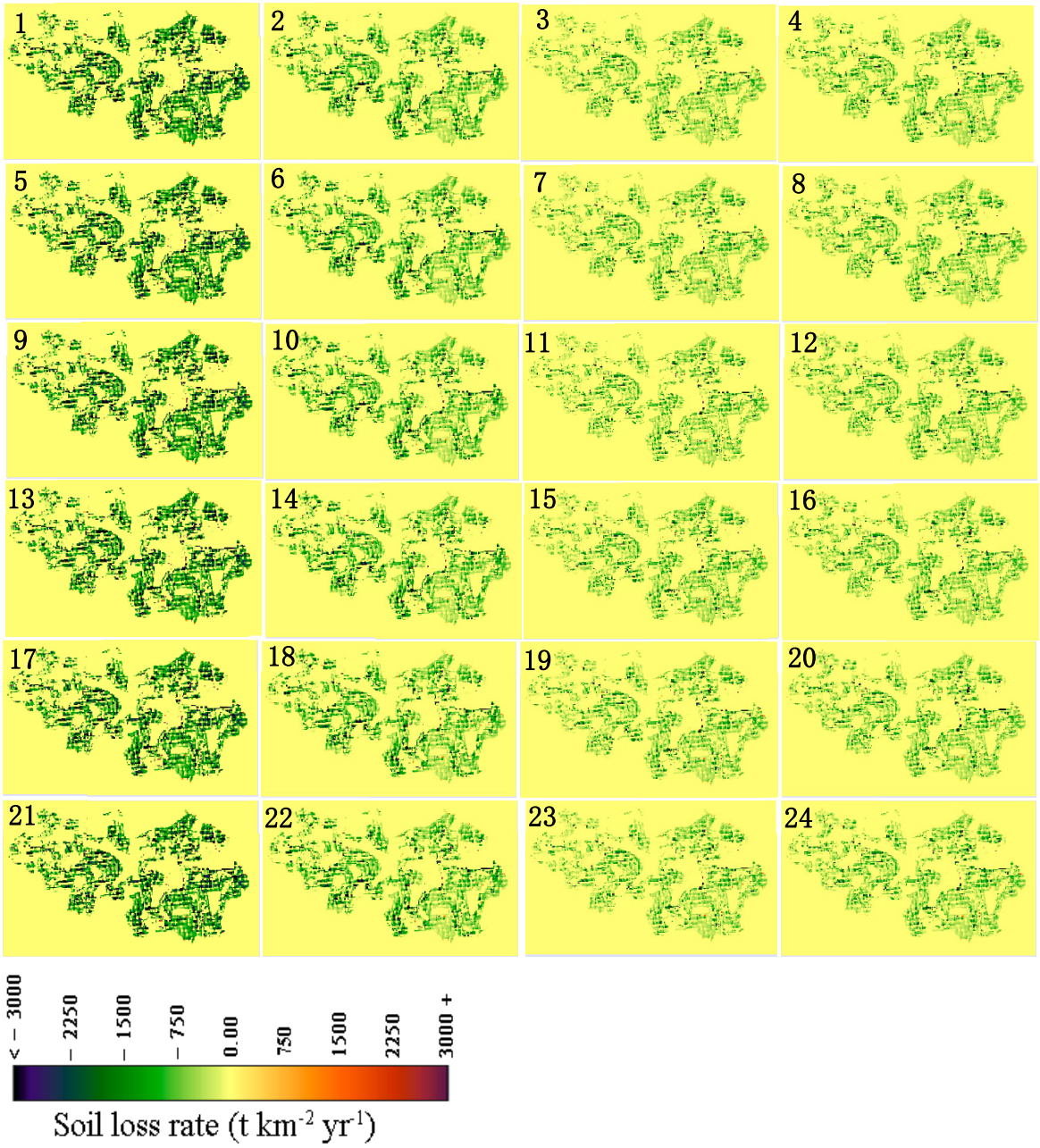

Figure 3. Spatial distribution of soil erosion and sediment deposition in the Qixin catchment under the 24 land use scenarios in Table 1. Note: the number represents scenario sequence. For example, 1 represents scenario 1, and 24 represents scenario 24.

Similarly to the changed pattern of SLRs, SYs under different scenarios also stepped down. The SYs under scenarios 1, 5, 9, 13, 17, and 21, with UD slopes, were the highest, ranging from 232 to 240 t km^{-2} yr^{-1}, and the scenarios 3, 7, 11, 15, 19, and 23 produced the lowest SSYs, ranging from 93.14 to 97.17 t km^{-2} yr^{-1}.

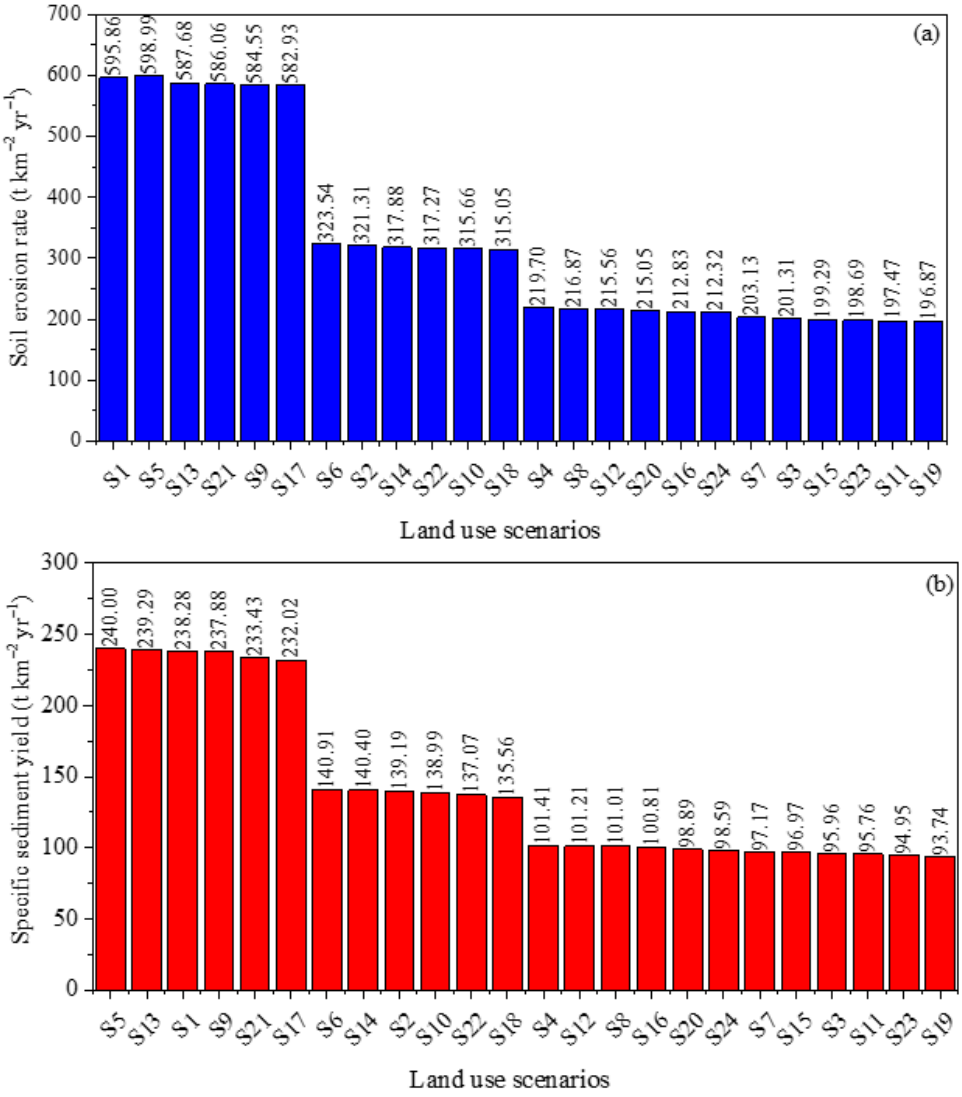

Figure 4. Soil erosion rate (**a**) and specific sediment yield (**b**) under the 24 land use scenarios in Table 1.

3.2. Sediment Delivery Ratio

The sediment delivery ratio (SDR) is the ratio of SY-to-SLR in a catchment. Different SDRs occurred under the 24 scenarios, with values ranging from 39.83% to 48.66% (Figure 5). The changing pattern of SDRs under different scenarios is opposite to those of SLRs, i.e., higher SLRs usually corresponded to lower SDRs. The largest SDR occurred under scenario 15, and the least SDR occurred under scenario 17.

3.3. Efficiencies of Catchment Managements

In contrast to the baseline scenario, the soil erosion control efficiencies varied from 0.52% to 67.13%, which occurred under scenarios 1 and 19, respectively. There were 12 scenarios that had above 60% control efficiencies, and 18 conservation scenarios with control efficiencies above 40%. The scenarios 1, 9, 13, 17, and 21 had lower control efficiencies.

In respect of SY, the control efficiencies ranged from 0 to 60.94%. Most of them were above 40%, and there were 12 scenarios with control efficiencies above 55% (Figure 6).

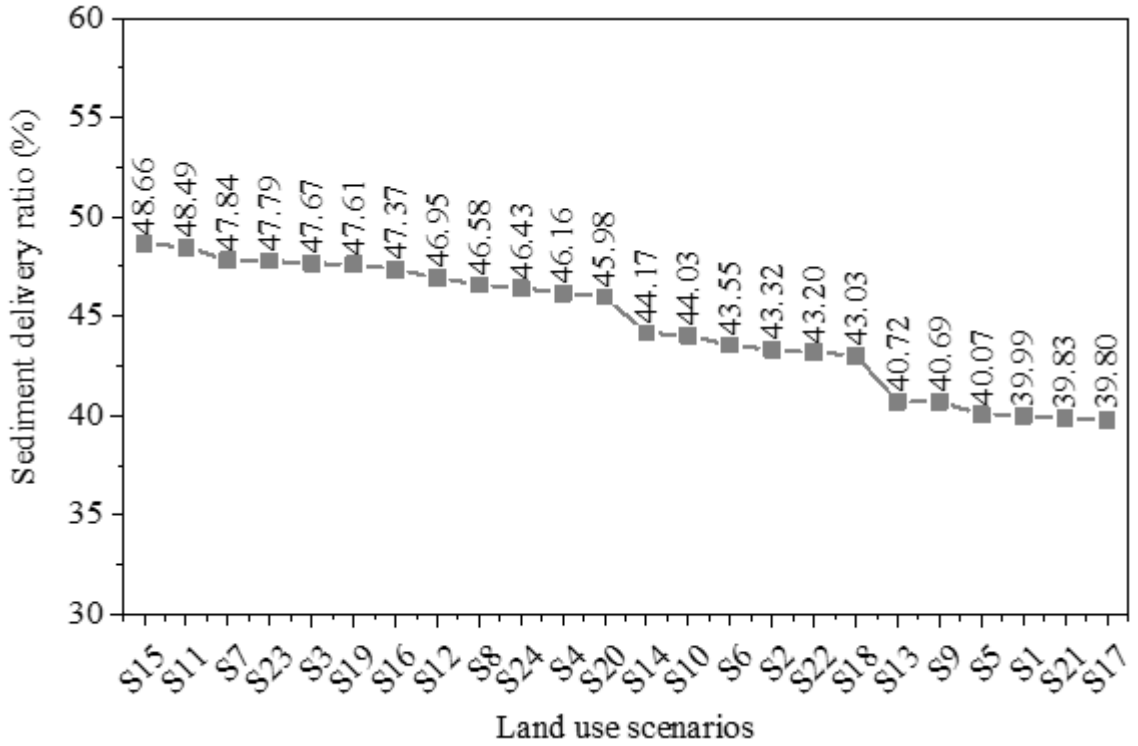

Figure 5. Changes in sediment delivery ratios with different land use scenarios.

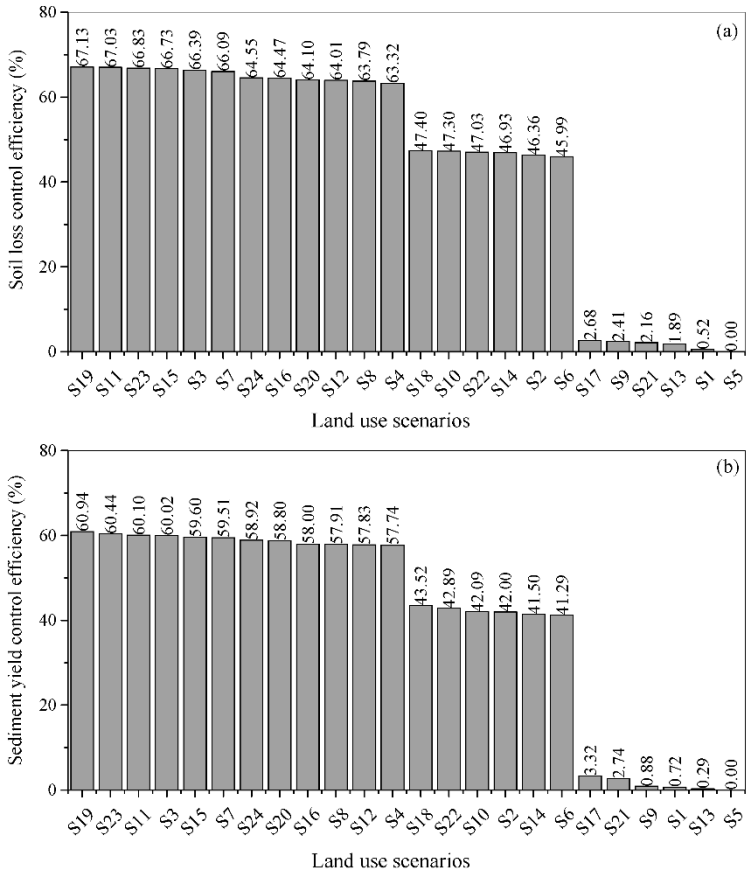

Figure 6. Soil erosion control efficiencies (**a**,**b**) sediment yield control efficiencies under the 24 soil conservation scenarios.

4. Discussion

4.1. Effect of Land Use and Topography

Agricultural land is the major sediment source area, and around 80% of agricultural lands in the world are suffering from moderate to severe soil erosion [42,43]. In the Qixin catchment, around one half (i.e., 49.5%) of the catchment area that is located on the slopes with a gradient less than 3° was cultivated (Figure 2c). When these cultivated lands were implemented with soil conservation measures, sharp decreases in SLR and SY occurred (Figure 4a,b).

Topographic factors, such as slope gradient, curvature, and slope length, are usually regarded as the main factors controlling soil loss. However, weak relations of soil erosion with slope gradient and curvature existed in the study region [10] and other regions in the world [44,45]. In contrast, the long slopes with UD cultivation can accumulate more runoff and a higher runoff capacity to detach soil erosion, as found by Cui et al. [46]. Therefore, although the slope gradient was gentle, intense soil erosion still occurred under scenarios 1, 5, 9, 13, 17, and 21.

4.2. Effect of Conservation Measures

The soil conservation measures on slopes were effective in reducing soil loss, which has been demonstrated on the Chinese Loess Plateau [8], in the Miyun Reservoir catchment [47], and in other regions of the world (e.g, Maetens et al. [48]). For example, in the Miyun reservoir catchment, in Beijing, the sediment control efficiency of terraces was above 99% [47].

In the present study, the effects of trenches and dams on soil loss and sediment yield were relatively lower. For example, scenarios 6, 14, and 22 had the same soil conservation measures on slopes, with different measures in gullies. In contrast to the baseline scenario 5, their soil loss control efficiencies were 45.99%, 46.93%, and 47.03%, respectively. In respect of S22, the relative contributions of soil loss and SY reductions by slope measures were 97.78% and 96.26%, respectively. The SY reduction efficiency was higher than that derived from the fingerprinting method by Fang [33] in the study region. This could be because more soil conservation measures were considered in the present study. However, the predicted SDR was still higher than the reported values in the study area [21,24,49]. However, if the STE of the Qixin Reservoir was considered, the SDR of this catchment was comparable to the reported values.

4.3. Limitations and Implications

WaTEM/SEDEEM cannot predict gully and river bank erosion, and stream incision [24]. This could underestimate catchment SY. Fang [23] found that the sediment from gullies and/or channels occupied around 49% of the total, which could underestimate the SY trap efficiencies of the measures, as mentioned in Section 4.2. However, it should be noted that the dams have an instantaneous impact on SY over a restricted time period [50–52]. With time duration, the sediment deposited in dams decreased due to decreasing sediment trap capacity [40]. In the study area, the useful time of the small dams is only around 8–10 years [23]. Tranches can be used to control slope and gully erosion. In Africa, studies [16] found that short trenches in the grassland can reduced runoff by 55%, and the efficiencies of soil loss control were higher when they were used with stone bunds in crop land. In the Chinese Loess Plateau, they are usually implemented in front of the gully head to control gully erosion [18]. Therefore, reasonable implementation and design of the trenches could also play an important role in reducing soil loss. High-resolution remote sensing data, with a physically based soil erosion model that can model gully or trench erosion, could better improve our understanding of their role in controlling soil erosion.

In the present study, all the estimated SLRs under scenarios 11, 15, 19, and 23 were lower than the tolerable value of 200 t km^{-2} yr^{-1}. Therefore, it seems that all the supposed catchment management scenarios are acceptable. However, deep insight found that the

estimated SLRs on the cultivated land with slope gradient less than 3° were still higher than 200 t km^{-2} yr^{-1} (Table 3). This can be explained by various reasons. The first is that the RUSLE-P value was overestimated, which resulted in a higher SLR. The second explanation is that the implemented soil conservation measures on the <3° slopes cannot indeed effectively control soil loss. Therefore, they should be redesigned or some measures should be further implemented on the slopes. Furthermore, because the trenches and dams in the catchment did not effectively control soil loss, more measures in gullies should be implemented in the study area.

Table 3. Soil erosion rates (t km^{-2} yr^{-1}) of different land use types under land use scenarios 11, 15, 19 and 23.

	Forest Land	Grass Land	Cultivated Land on Different Slopes (°)			
			0–3	3–5	5–8	>8
S19	53.70	14.23	−218.57	−109.44	−199.82	−17.44
S11	53.70	14.23	−218.57	−109.44	−199.82	−17.44
S23	50.04	14.85	−222.74	−65.05	−177.03	−194.37
S15	50.04	20.35	−227.97	−66.12	−177.03	−194.31

Note: The minus represents soil erosion, and the positive value represents sediment deposition.

5. Conclusions

In the present study, the integrated catchment managements (i.e., three defensing lines) were evaluated based on 24 scenarios. The present study found that the current conservation measures (i.e., scenario 5) cannot effectively control soil loss, with a catchment SLR of 598.99 t km^{-2} yr^{-1} and SY of 240.00 t km^{-2} yr^{-1}, mostly resulting from the large area of <3° slopes without any soil conservation measures. In contrast, the S19 with contour tillage on <3° slopes, hedgerow planting on 3–5° slopes, terracing on 5–8° slopes, and forestation on >8° slopes, trenches along the forest, and dam construction in gullies can effectively control soil loss, with a catchment SLR that is less than the tolerable value. However, the SLR on the <3° slopes was still higher than the tolerable value of the study region.

For the best catchment management scenario 19, the soil conservation measures on the slopes contributed to the over 95% soil loss reduction, while the trenches and dams in gullies only trapped less than 5% of sediment from the catchment. The CT measure should be redesigned or some measures should be further implemented on the <3° slopes with CT measures, and more measures should be implemented in gullies to prevent sediment flowing out of the catchment.

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