Potential Effects of Climate Change on Rainfall Erosivity in the Yellow River Basin of China

G.-H. Zhang, M. A Nearing, B.-Y. Liu

Abstract. *Severe soil erosion in the Yellow River basin is a significant obstruction to the sustainable management of soil and water resources. Any changes in soil erosion will have great effects on long-term planning of soil and water conservation in such a severely eroded basin. Rainfall erosivity describes the soil loss potential caused by rain, which can be expected to change in correspondence to changes in climate. This study was conducted to assess the potential effects of climate change on rainfall erosivity in the Yellow River basin. Two different rainfall scenarios were generated with the HadCM3 general circulation model for the years 2006 to 2035, 2036 to 2065, and 2066 to 2095. The statistics test showed that rainfall erosivity increased significantly in the Yellow River basin under both scenarios for all periods in the coming decades. The erosivity increase varied from scenario to scenario, and from period to period. Generally, increases in erosivity were less from southeast to northwest. The calculated precipitation elasticity of rainfall erosivity indicated that percent changes in rainfall erosivity were greater than percent changes in total precipitation by a factor of 1.2 to 1.4. The expected increases in precipitation require that more attention will be given to soil and water conservation practices such as vegetation rehabilitation and check-dam construction.*

Keywords. *GCM, Precipitation, Soil and water conservation, Soil erosion.*

Climate changes resulting from greenhouse gas-induced global warming are expected to influence the extent, frequency, and magnitude of soil erosion by water in several ways (Williams et al., 1996). Changes in atmospheric CO_2 concentrations, temperature, precipitation, and humidity can be expected to influence, for example, plant biomass production, plant residue decomposition rates, soil microbial activity, evapotranspiration rates, and soil surface sealing and crusting. Each of these factors influences erosion rates (Nearing, 2001). Soil erosion can also be expected to change with shifts in land use and management designed to accommodate new climate regimes caused by global climate change (Favis-Mortlock and Guerra, 1999).

Any changes in precipitation, whether in amounts of rain per event, rainfall intensity, precipitation frequency, or seasonal rainfall patterns, may directly influence erosion rates (Favis-Mortlock and Boardman, 1995; Pruski and Nearing, 2002). An increasing frequency of intensive rainfalls may be accompanied by a clustering of dry periods, which represents a dangerous combination with regard to water erosion (Sauerborn et al., 1999). Dry soils are much more susceptible to water erosion than moist soils because infiltration water compresses the air in soil aggregates, destabilizing them and causing their breakdown. Subsequently, the soil particles can easily be carried away by the same account of surface runoff (Sauerborn et al., 1999).

However, the most direct effect of climate change on erosion by water can be expected to be the effect of changes in rainfall erosivity. Sauerborn et al. (1999) found that rainfall erosivity of the north Rhine-Westphalia area of Germany was expected to increase under future climatic scenarios. Based on the relationship between erosivity (R factor) and modified Fournier's index (Arnoldus, 1980), proposed by Renard and Freimund (1994), Nearing (2001) assessed the potential changes in rainfall erosivity across the U.S. in the 21st century under two coupled atmosphere-ocean global climate models. The results indicated the potential for great changes in rainfall erosivity across the continental U.S.

The Yellow River is the largest river in northern China (fig. 1). It flows east for 5,464 km with a drainage area of 752,443 km^2. The mean annual precipitation is 436 mm, which decreases from the southeastern to northwestern parts of the Yellow River basin (fig. 2). In most regions, more than 70% of precipitation falls during the months of June through October. The upper part of the drainage basin is located on the Qinhai-Tibet Plateau, the middle part on the Loess Plateau, and the lower part in the North China Plain (Xu and Cheng, 2002).

Runoff varies from region to region. In the upper reach (west of Lanzhou, fig. 1), the runoff is greater compared to the region of Lanzhou to Toudaoguai due to lower evapotranspiration. More than 60% of runoff to the Yellow River originates in this region (table 1). The average annual runoff is only 1.75 mm in the region of Lanzhou to Toudaoguai due to lower precipitation, higher evapotranspiration, sandy soil, and lower slope. Soil erosion in most areas of the middle

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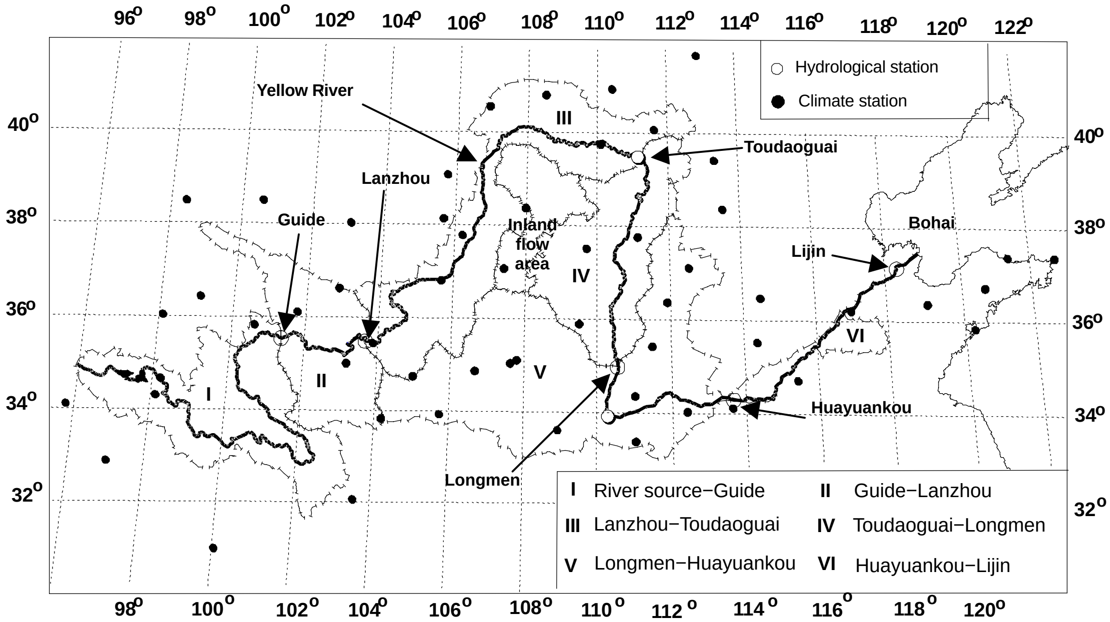

Figure 1. Yellow River map showing the six sub-basins and climate and hydrological stations.

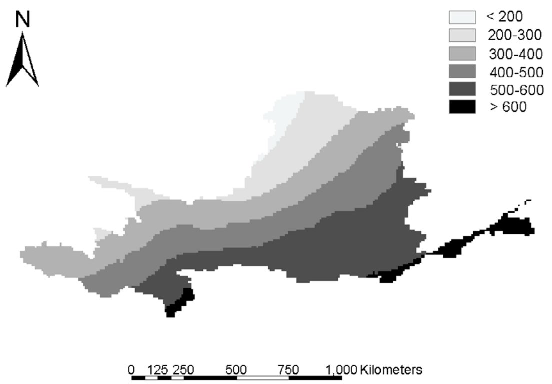

Figure 2. The 30-year observed mean annual precipitation in the Yellow River basin (1961-1990).

reach of the Yellow River (the Loess Plateau) reaches 5,000 to 10,000 t km^{-2} $year^{-1}$ due to various gullies, intensive storms, erodible loess soil, minimal vegetative cover, poor land use, and human activities, especially in the region of Toudaoguai to Longmen (Qian et al., 1980; Mi, 1982; Liu, 1984; Fu and Gulinck, 1994; Tang et al., 1998). The result of such serious erosion is approximately 1.6 billion tons of suspended sediment load transported to the lower reach of the Yellow River annually (east of Huayuankou), of which 0.4 billion tons are deposited in the channel. The deposited sediment causes an annual rise of 8 to 10 cm in the channel bed (Shi and Shao, 2000).

The objective of the current study was to estimate the potential change in rainfall erosivity in the Yellow River basin of China by the years 2020, 2050, and 2080 under two climatic change scenarios generated from the HadCM3 general circulation model (GCM).

Methods

Rainfall erosivity (*R* factor) describes the soil loss potential caused by rainfall. It was calculated from two rainfall characteristics: total kinetic energy of the storm times its 30 min intensity (EI_{30}). This product reflects the combined potential of rainfall impact and turbulence of runoff to transport dislodged soil particles from the field (Wischeimer and Smith, 1978). A direct computation of rainfall erosivity requires long-term data for both rainfall amounts and intensities (Renard et al., 1997).

However, rainfall intensity is not provided by current GCMs. Therefore, relationships between rainfall erosivity and monthly or annual precipitation were developed and used to analyze the potential effects of climate change on rainfall erosivity (Renard and Freimund, 1994; Sauerborn et al.,

Table 1. Six sub-basins of the Yellow River basin.[a]

Sub-basin Number	Sub-basin Name	Area (km^2)	Precipitation (mm $year^{-1}$)	Runoff (mm $year^{-1}$)	Sediment (10^8 t $year^{-1}$)
I	River source-Guide	133,775	424.2	171.4	0.254
II	Guide-Lanzhou	88,776	403.5	144.2	0.595
III	Lanzhou-Toudaoguai	163,415	292.3	1.8	0.602
IV	Toudaoguai-Longmen	111,595	447.0	52.0	8.161
V	Longmen-Huayuankou	232,475	527.3	80.6	2.658
VI	Huayuankou-Lijin	22,407	649.9	49.1	−1.778
Total	Yellow River basin	752,443	436.0	82.0	10.492

[a] Precipitation and runoff are the means of 1961 to 1990, and sediment is the mean of 1951 to 1985.

1999; Nearing, 2001). In order to analyze the spatial distribution of rainfall erosivity, Wang and Jiao (1996) developed a simple equation for R value on the Loess Plateau based on nine evenly distributed stations, which have long-term daily precipitation data. The R values were calculated using the method described by Wischeimer and Smith (1978):

$$R = 0.196\, P^{1.03} {I_{60}}^{0.971} {I_{1440}}^{0.313} \qquad (1)$$

where R is rainfall erosivity (MJ mm ha^{-1} year^{-1}), P is mean annual precipitation (mm), I_{60} is the maximum 60 min rainfall (mm), and I_{1440} is the maximum 1440 min rainfall (mm).

The rainfall erosivity of 164 climatic and hydrological stations across the Loess Plateau was calculated using equation 1, which is available in the literature (Wang and Jiao, 1996). The 31-year (1955 to 1986) mean annual precipitation and rainfall erosivity of those stations were used to develop the relationship between rainfall erosivity and precipitation for the Yellow River basin of China. Because few stations were located in the lower reach of the Yellow River basin (east of Lanzhou, fig. 1), the same relationship was adopted for the middle and lower reaches. Although this relationship may have caused a small error in rainfall erosivity estimation for the lower reach, it can still be used in the current study to analyze the potential effects of climate change on rainfall erosivity because only 3% sediment of the Yellow River originates in this region.

For the upper reach (west of Lanzhou):

$$R = 1.0841\, P^{1.3683},\ r^2 = 0.89 \qquad (2)$$

For the middle and lower reach:

$$R = 5.3595\, P^{1.2396},\ r^2 = 0.65 \qquad (3)$$

where R is rainfall erosivity (MJ mm ha^{-1} year^{-1}), and P is mean annual precipitation (mm).

The Yellow River basin was delimited into six sub-basins based on potential for runoff and soil erosion (fig. 1). Annual precipitation from 1961 to 1990 and 30-year mean annual precipitation (referred to as the 30-year observed mean annual precipitation) were calculated for each of 56 stations within and around the Yellow River basin based on measured monthly precipitation.

Various atmospheric GCMs are currently used to simulate climatic sensitivity to increased carbon dioxide concentrations and other important parameters. Some of the leading GCMs in common use are: HadCM (Hadley Centre for Climate Prediction and Research), CCCM (Canadian Center for Climate Modelling and Analysis), NCAR-CSM (National Center for Atmospheric Research), and ECHAM (Max Planck Institute for Meteorology) (Loaiciga et al., 1996). Although the basic theory of these models is similar, the simulated rainfall erosivity and erosion rates are inconsistent in some regions under different GCM models (Favis-Mortlock and Guerra, 1999; Nearing, 2001). For the current study, the commonly used HadCM3 GCM was chosen to generate the future precipitation scenarios.

HadCM3 is the third generation of atmosphere-ocean global climate models produced by the Hadley Centre. It simulates a 1% increase in greenhouse gases for the time period studied, as well as the effects of sulfate aerosols. The model also considers the effects of the minor trace gases CH_4, N_2O, CFC11, CFC12, and HCFC22, and includes several

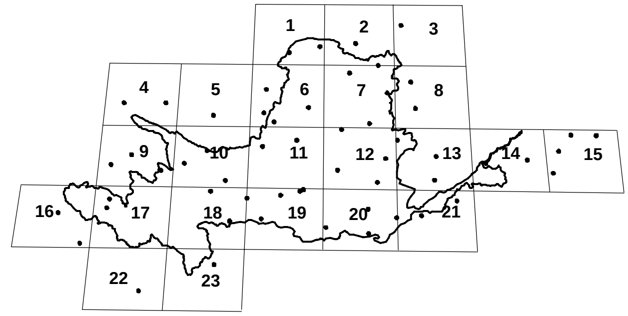

Figure 3. GCM output grids used in current study.

improvements over the previous Hadley Centre model, HadCM2. The simulated results from the model are reported on a 2.5° latitude by 3.75° longitude grid (Gordon et al., 2000; Pope et al., 2000). Twenty-three grids were used in the current study (fig. 3).

Two scenarios were used in the current study to represent the different future societies. Scenario A2 represents a heterogeneous world, strengthening regional cultural identities, with an emphasis on family values and local traditions, high population growth, and less concern for rapid economic development. Scenario B2 defines a heterogeneous world with less rapid, and more diverse technological change, but a strong emphasis on community and social innovations to find local, rather than global, solutions (IPCC, 2001).

Climate change scenarios were taken from the grid output of HadCM3 for both the A2 and B2 scenarios (IPCC (2001). The 30-year monthly precipitation was extracted from the IPCC data center (http://ipcc-ddc.cru.uea.ac.uk/) for the periods 1961 to 1990 (representing the baseline), 2006 to 2035 (the 2020s), 2036 to 2065 (the 2050s), and 2066 to 2095 (the 2080s). The 30-year mean annual precipitation was calculated for the different periods for each GCM grid.

Generally, the simulated results of a GCM cannot used directly to simulate the impact of climate change on soil erosion due to the coarse resolution (typically of the order of 50,000 km^2) of the GCM grids. It is impossible to resolve important sub-grid-scale features such as clouds, vegetation, land use, and topography, which strongly influence soil erosion. Thus, a downscaling procedure is necessary to combine the simulated results of the GCM with local-scale studies. However, the downscaling results are inconsistent between four normally used downscaling techniques (Wilby et al., 2002; Xu, 1999).

In the current study, the delta change method was used to estimate the potential change in climate (Arnell, 1996; Hay et al., 2000). The percent differences in the 30-year mean annual precipitation between the baseline (1961 to 1990) and future GCM simulations (the 2020s, 2050s, and 2080s) were computed for each GCM output cell. The same percent was used for the stations within the same GCM output grid (fig. 3). The potential change in precipitation for each station was the product of the calculated change (in percent) multiplied by the 30-year observed mean annual precipitation. The precipitation values for 56 stations were interpolated into small grids (0.1° × 0.1°) by kriging (Oliver and Webster, 1990) to obtain the regional precipitation for both the current and future scenarios. The rainfall erosivity of each station was calculated based on equations 2 or 3 and then interpolated by the same method used for regional precipitation to obtain the regional rainfall erosivities under different climate scenarios. The regional values of precipitation and rainfall erosivity were the simple average values of the small grids within the sub-basin. T-tests were conducted for the six sub-basins between the current and future rainfall erosivity to determine whether the potential changes in rainfall erosivity were significant.

Schaake (1990) introduced the concept of elasticity for evaluating the sensitivity of runoff to changes in climate. This concept can also be used to evaluate the sensitivity of rainfall erosivity to changes in precipitation. Precipitation elasticity of rainfall erosivity, $\varepsilon_p(P,R)$, can be defined as the proportional change in rainfall erosivity (R) divided by the proportional change in precipitation (P) (Sankarasubramanian et al., 2001):

$$\varepsilon_p(P,R) = \frac{dR/R}{dP/P} = \frac{dR}{dP}\frac{P}{R} \qquad (4)$$

Results and Discussion

The regional changes in mean annual precipitation are shown in table 2. Compared to table 1, it is clear that the 30-year mean annual precipitation generated by the GCM was greater than the observed 30-year mean annual precipitation for 1961 to 1990 across the Yellow River basin for both the A2 and B2 scenarios. For the A2 scenario, the mean annual precipitation continually increased from period to period. However, for the B2 scenario, there was a greater increase for the years 2006 to 2035. It declined for the years 2036 to 2065, and then increased again for the years 2066 to 2095. Such changes in rainfall will lead to corresponding changes in rainfall erosivity.

The regional potential changes in rainfall erosivity are given in table 3. The results of statistic analysis indicated that significant changes in rainfall erosivity could be expected across the Yellow River basin for both the A2 and B2 scenarios in the coming century (table 4). The potential changes in rainfall erosivity were different from scenario to scenario, and varied from period to period.

The potential changes in rainfall erosivity under future GCM scenarios are plotted in figures 4 and 5. Erosivity results estimated for scenario A2 indicated a general increase in rainfall erosivity across the Yellow River basin (fig. 4). The increase in rainfall erosivity of the Yellow River basin (area weighted value) was 8.5%, 22.1%, and 34.5% by the year 2020, 2050, and 2080, respectively. Rainfall erosivity calculated from scenario B2 also showed an increase over the Yellow River basin (fig. 5). The increase in rainfall erosivity of the Yellow River basin (area weighted value) was 18.2%, 11.5%, and 19.3% by the year 2020, 2050, and 2080, respectively. Compared to scenario B2, the range of changes in rainfall erosivity simulated by scenario A2 was lower in the years 2006 to 2035 and greater in the other two periods, especially in the years 2066 to 2095 (figs. 4 and 5).

The general spatial trend was that changes in rainfall erosivity decreased from the southeast to the northwest. In the upper reach of the Yellow River basin (west of Lanzhou), the increase in rainfall erosivity decreased from east to west. The minimum value of increase in rainfall erosivity always appeared in the west, and the maximum value of increase was always in the east.

Table 2. Mean annual precipitations under different scenarios (mm).

Sub-basin	A2 2020	A2 2050	A2 2080	B2 2020	B2 2050	B2 2080
I	433.5	468.8	489.8	459.3	441.2	463.7
II	413.7	457.4	476.1	441.0	418.6	451.7
III	329.9	336.8	378.2	333.2	320.1	328.4
IV	486.6	571.5	627.0	530.1	505.3	539.8
V	556.5	607.5	647.2	604.0	577.8	607.3
VI	677.5	784.0	872.0	740.3	685.3	759.9

Table 3. Rainfall erosivity of each sub-basin under different scenarios (MJ mm ha^{-1} year^{-1}).

Sub-basin	1961-1990	A2 2020	A2 2050	A2 2080	B2 2020	B2 2050	B2 2080
I	4269	4398	4895	5198	4760	4505	4823
II	3987	4126	4733	5000	4503	4193	4653
III	6106	7094	7279	8404	7182	6834	7054
IV	10338	11485	14019	15726	12771	12035	13062
V	12688	13564	15122	16356	15014	14211	15116
VI	16441	17311	20745	23669	19322	17558	19958

Table 4. T-test of potential changes in rainfall erosivity under different scenarios (0.05).[a]

		A2 2020	A2 2050	A2 2080	B2 2020	B2 2050	B2 2080
1961-1990		SD	SD	SD	SD	SD	SD
A2	2020	--	SD	SD	SD	SD	SD
	2050	--	--	SD	SD	SD	SD
	2080	--	--	--	SD	SD	SD
B2	2020	--	--	--	--	SD	SD
	2050	--	--	--	--	--	SD
	2080	--	--	--	--	--	--

[a] SD represents a significant difference.

The calculated precipitation elasticity of rainfall erosivity under different scenarios is shown in table 5. It is clear that the precipitation elasticity of rainfall erosivity varied little, remaining within the range of 1.17 to 1.39. This result indicated that changes in precipitation were always amplified in rainfall erosivity, since the precipitation elasticity of rainfall erosivity was greater than unity across the Yellow River basin.

According to the USLE, a 1% increase in rainfall erosivity will lead to a 1% increase in soil erosion, if other factors remain constant. The simulated results of the current study indicated that the rainfall erosivity might increase significantly across the Yellow River basin, especially in the middle and lower reach, in the coming century. Thus, soil erosion of the Yellow River basin would increase due to increased rainfall erosivity. The expected increase in soil erosion in the Toudaoguai-Longmen region is important for long-term planning of soil and water conservation, since more than 75% of the sediment in the Yellow River basin originates from this region (table 1).

Two principal measures used in the Yellow River to control soil erosion are planting and engineering. However, water is the limiting factor for vegetative growth in most areas of the Yellow River basin, especially in the Loess Plateau (Yang and Shao, 2000). The expected increase in precipitation caused by global climate change may have positive effects on vegetative rehabilitation in the Yellow River basin. This change may affect other factors, such as

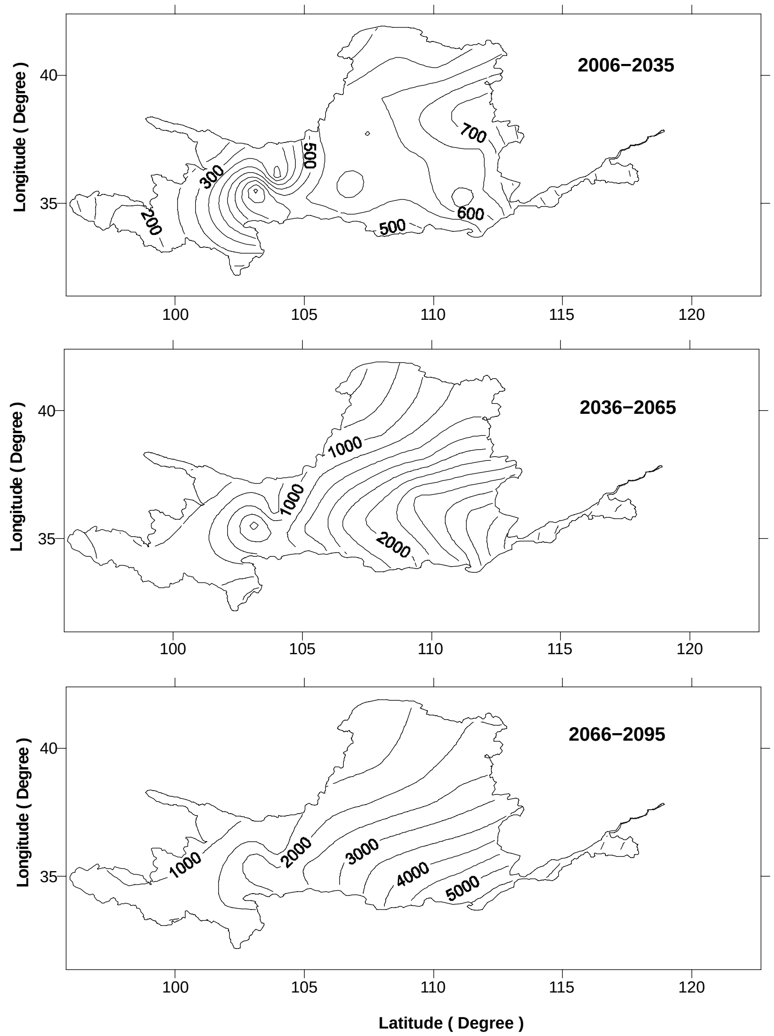

Figure 4. Potential change in rainfall erosivity under the A2 scenario.

protective cover (*C* in USLE). Improved vegetation conditions will lead to a decrease in the cropping factor (*C*), resulting in a somewhat lower soil erosion rate than would otherwise be the case.

Check-dams are the most widespread engineering structures used for conserving soil and water in the Loess Plateau (Xu et al., 2004). According to the Plan of Soil and Water Conservation for the Loess Plateau, approximately 163,000 check-dams will be built in the next 20 years. The total investment is expected to be approximately 10 billion dollars. More than 102,800 check-dams will be constructed in the Toudaoguai-Longmen region. The expected increases in soil erosion will lead to more sediment transported in gully systems, which may have significant effects on check-dam construction. For example, the deposition rate behind check-dams will increase, and thus the time needed for check-dams to fill will decrease. For the long-term, the land use and farming systems may be changed to adapt to the changed climate conditions (Favis-Mortlock and Guerra, 1999), which will lead to complex changes in soil erosion in the Yellow River basin. More related studies are needed to evaluate the comprehensive effects of climate change on soil erosion in the Yellow River basin.

The increase in precipitation can be expected through the increase in the number of rain days and the increase in rainfall intensity. The study conducted by Pruski and Nearing (2002) indicated that changes in rainfall that occur due to changes in storm intensity can be expected to have a greater impact on erosion rates than those due to changes in the number of rain days alone. However, rainfall intensity is not provided by current GCMs. Further studies are necessary to consider the impact of rainfall intensity on potential changes in rainfall erosivity and soil erosion in the Yellow River basin.

Conclusions

A relationship between rainfall erosivity and annual precipitation was extended to obtain an estimate of changes in erosivity due to the potential change in precipitation in the Yellow River basin of China. The relationship was developed based on data in the literature (Wang and Jiao, 1996) to investigate the potential effects of precipitation change on rainfall erosivity.

In general, the simulated results showed significant increases in rainfall erosivity across the Yellow River basin for both scenarios A2 and B2 in the coming century. The erosivity increase varied from scenario to scenario, and from period to period. The general trend of increases in erosivity was less from southeast to northwest. The average increases

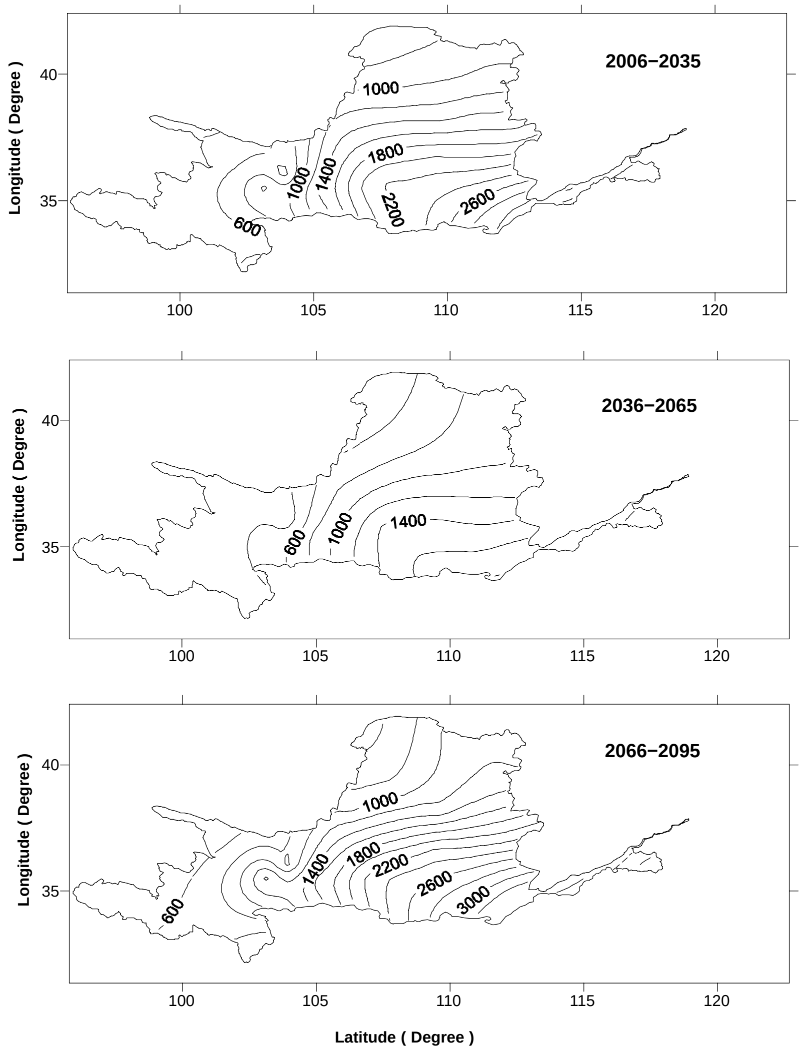

Figure 5. Potential change in rainfall erosivity under the B2 scenario.

Table 5. Precipitation elasticity of rainfall erosivity under different scenarios.

Sub-basin	A2			B2		
	2020	2050	2080	2020	2050	2080
I	1.38	1.39	1.38	1.32	1.36	1.38
II	1.38	1.39	1.38	1.31	1.36	1.39
III	1.26	1.25	1.26	1.18	1.23	1.25
IV	1.25	1.26	1.25	1.17	1.23	1.25
V	1.25	1.25	1.25	1.20	1.23	1.26
VI	1.25	1.26	1.26	1.17	1.23	1.26

in rainfall erosivity in the Yellow River basin were 8.5%, 22.1%, and 34.5% for scenario A2 and 18.2%, 11.5%, and 19.3% for scenario B2 by the year 2020, 2050, and 2080, respectively. The precipitation elasticity of rainfall erosivity varied within the range of 1.17 to 1.39. This indicated that percent changes in rainfall erosivity were greater than percent changes in total precipitation.

These results imply that soil erosion in the Yellow River basin may be expected to be more serious in the coming decades. The expected increase in precipitation may have significant effects on soil and water conservation in the Yellow River basin for both vegetation rehabilitation and check-dam construction. More studies are necessary to investigate the comprehensive effects of climate change on soil erosion and soil conservation in the Yellow River basin.

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