Potential Impacts of Climate Change on Rainfall Erosivity and Water Availability in China in the Next 100 Years

***Ge Sun*[1], *Steven G. McNulty*[2], *Jennifer Moore*[2], *Corey Bunch*[1] and *Jian Ni*[3]**

[1]North Carolina State University, 920 Main Campus Dr., Venture II, Suite 300, Raleigh, NC 27606,USA.
E-mail: Ge_Sun@ncsu.edu
[2]Southern Global Change Program, USDA Forest Service, 920 Main Campus Dr., Venture II, Suite 300, Raleigh, NC 27606, USA
[3]Max Planck Institute for Biogeochemistry, Carl Zeiss Promenade 10, P.O. Box 100164, D-07701 Jena, Germany

Abstract: Soil erosion and water shortages threaten China's social and economic development in the 21st century. This paper examines how projected climate change could affect soil erosion and water availability across China. We used both historical climate data (1961—1980) and the UKMO Hadley3 climate scenario (1960—2099) to drive regional hydrology and soil erosivity models. The GCM predicts that eastern, and central China will experience a hotter and drier climate in the next 30 years. Available water could decrease by 20%. Rainfall erosivity is expected to increase significantly in northeastern and southeastern China. During 2061—2099, both air temperature and precipitation are expected to increase greatly across China. Consequently, rainfall erosivity for the soil erosion prone regions, the Yellow and Yangtze River basins and northeastern China, are expected to increase significantly. Soil erosion control will continue to be a challenge for these regions in the 21st century. Although more water will become available for most of China during the second half of this century, northern China is expected to experience more water stress due to large increases in temperature.
Keywords: China, climate change, evapotranspiration, soil erosion, water resources

1 Introduction

Water is the most precious natural resource in China and water shortages have become one of the major environmental challenges to China's modernization in the 21st century. Nationally the total amount of usable surface and ground water is about 2,800 km^3 or half of annual precipitation. This volume of water represents about 6% of the global water supply. However, China contained 22% of the global population in 1997. Therefore, on a per capita basis, China has only 2,220 m^3/person, or 25% of the world's average. It is estimated that by 2,030 the population is expected to reach 1.6 billion. China will be water stressed as defined by the international standard of 1,700 m^3/person (Qian and Zhang, 2001). More than 110 Chinese cities are suffering from a severe water shortage due to a lack of resources, water pollution and deterioration of the environment. Irrigation in China is at least double that of the United States and it is perhaps the most important priority in water resource policy, with hydropower ranking second and flooding ranking third. Little attention has been given to ecological water uses by natural ecosystems (Shen and Wang, 2001).

Several causes responsible for the water crisis have been identified (Qian and Zhang, 2001). Water pollution from point and non-point sources, uneven distribution of water resources, overconsumption of water resources, and a lack of water-saving technology are among the major factors.

Recently released national survey on soil erosion by China's Ministry of Water Resources reported that 37% (3.6 million km^2) of the land area was classified as having soil erosion problems, either due to water (46%) or wind (53%) forces. Most of the areas with water erosion lie in the western hilly regions of the upper reaches of the Yangtze River and middle reaches of Yellow River which are relatively undeveloped in China. A new survey by the State Forestry Administration suggests that 2.7 million km^2 or 28% of land in China is desert. Northern and western parts of China were the most vulnerable, including the autonomous regions of Inner Mongolia, Tibet and Xinjiang, and the northern provinces of Hebei and Shanxi. Persistent droughts caused by global warming and human activities of over-cultivation, overgrazing, deforestation, and poor irrigation practices were believed to be responsible to the increase in desert area. Soil erosion causes non-point source pollution and is the major factor degrading water quality.

Over 80% of China's water supply is concentrated in the southeastern part of China while less than 20% is available for the Northern regions. Some of the productive and populous northern regions, such as Huanghe, Huihe, and Haihe basins, only share 8% of the national total (500 m^3 per capita). This had made the problems more acute that the northern areas have experienced increasing levels of drought in recent years. Water stress is particularly severe in the major cities such as Beijing and Shanghai where groundwater supplies are almost exhausted. One strategy under investigation is to construct waterways to link the Yangtze River in the south to the Yellow River in the north.

Among other environmental problems (e.g dust storms, sea level rise) caused by climate change, climate change further aggregates water shortages in China. Studies on the potential effects of climate change on hydrology and water resources started in the mid-1980s when the IPCC was created with China being an active member. In the past ten years, China participated a series of assessment and regional modeling projects, including the GEWEX Asian Monsoon Experiment (GAME) program. Using historical climate data, Liu and Fu (1996) concluded that northern and eastern China (35^o N or 113^o — 117^o E) has warmed by 0.88 ^oC to 1.75 ^oC from the 1950s to 1980s. They found that precipitation had decreased for most part of the country. A recent review (Jiang *et al.*, 2000) concluded that streamflow in China is somewhat sensitive to temperature change, and very sensitive to precipitation. The dry northern regions that have been under serious water resource stress as discussed earlier are more sensitive than the humid south. Although watershed hydrologic patterns are not expected to change across climate zone lines, streamflow from those rivers fed by snow melt is expected to decrease. Deng (2001) reports that soil moisture in northern and northestern China will decrease under future climate change and suggests there is a urgent need on study the effects of climate and landuse change in China.

Therefore, this paper examines two important water quality and water quantity questions related to rainfall erosivity and water availability. Using a hydrolgic model and an erosivity model, we predict how the two variables will change under future climate change conditions. We discuss the implications to soil erosion control and sustainable development of China's water resources in the 21^{st} century.

2 Methods

2.1 The rainfall-runoff erosivity factor (r) model

The Universal Soil Loss Equation (USLE) and its successor Revised Soil Loss Equation (RUSLE) have been widely use throughout the world to estimate long-term soil erosion. Those empirical soil erosion models quantify soil erosion as the product of six major factors including rainfall and runoff erosivity (R), soil erodibility (K), slope length (L) and Slope Steepness (S), cover and management (C), and supporting conservation practices (P). Only R and K have units. In this paper, we use the US customary units of hundreds of foot tonf inch $arce^{-1} \cdot h^{-1} \cdot year^{-1}$, which can be converted from the SI unit MJ mm $\cdot ha^{-1} \cdot h^{-1} \cdot year^{-1}$ by dividing 17.02. The R factor in the US varies from <20 in the west coast to 550 in the Gulf of Mexico in the southeast. Renard and Freimund (1994) summarized various methods used throughout the world for calculating R values when site-specific rainfall intensity data are not readily available. We adopted the Fournier's Index method that is presented in Renard and Freimund (1994) and described below to estimate long-term R values across China under the historic and climate change scenarios. Nearing applied the same model to examine the effects of climate change on rainfall erosivity in the continental US (Nearling, 2001).

Using 132 US weather station data, Renard and Freimund (1994) derived the following regression equations to estimate R for rainfall-dominated regions.

$$R\text{–factor} = (0.07397\ F^{1.847})/17.2 \quad \text{when } F < 55 \text{ mm}$$

$$R\text{–factor} = (95.77–6.081*F+0.4770*F^2)/17.2 \quad \text{when } F >= 55 \text{ mm}$$

$$F = \frac{\sum_{i=1}^{12} P_i^2}{\sum_{i=1}^{12} p_i}$$

Where, P_i is monthly precipitation (mm/month) and F is modified Fournier coefficient.

2.2 Water availability

We define water availability or water yield as the difference between annual precipitation (P) and actual water loss by evapotranspiration (*AET*). Annual *AET* is estimated using a conceptual watershed *ET* model that has been validated in the US (Sun *et al.*, 2002) and around the world (Zhang *et al.*, 2001).

$$AET_i / P = \frac{1 + w_i \frac{PET}{P}}{1 + w_i \frac{PET}{P} + \frac{P}{PET}}$$

Then, Water Yield (Q) $= P - AET$

Where, *PET* is potential evapotranspiration estimated by the Hamon’s method; *w* is a model parameter reflecting the effects of landcover *i* (*i*=1 to 5) on water loss from *ET*. For this paper, we use *w*=2.8 for conifer forests, 2.0 for croplands. For deciduous forest, *AET* is reduced 20%. *AET* is approximated as 30% of annual *P* for urban areas. *AET* is assumed to be equal to the least of *P* and *PET* for water bodies and wetlands. For Urban or bare soils, *w* was set as 0.0. For mixed landuse/cover watersheds (1 km grid in this paper), *AET* represent the weighted average of AET_i for all landcover types.

We also compared the above model with an empirical model developed by Liu (1986), who used hydrologic data from over 100 watersheds in China.

$$Q = P - C * [1-\exp(-P/C)]$$

C is a parameter that varies from 800 for mountainous regions to 1100 for plains regions. The disagvantage of this static model is that it is not sensitive to landuse/landcover and climate changes.

3 Databases

Multiple scale regional databases with different resolution were acquired and constructed from various sources (Table 1). Data were compiled and manipulated to drive the erosivity and hydrology models. ‘Measured’ historic climate databases with a spatial resolution of 10 by 10 seconds, or approximately 16 by 16 km, were used to develop historic maps for both the erosivity (R) and water availability (Q). This database was also used to check the accuracy of the GCM scenario in predicting climate patterns for China. Outputs with coarser spatial resolution (2.5^o latitude by 3.75^o longitude approximately 220 by 340 km) from the Hadley Centre HadCM3 SRES climate change scenario were used to examine potential climate change and its effects on R and Q across the entire country. We understood that there are potential errors in the HadCM3 scenario in modeling the historic climate regimes. Therefore, we focused our analysis on the relative future changes of climate and their impacts on R and Q by using the Hadley3 predicted historic climate (1960—2000) as our baseline for analysis.

4 Results

4.1 Historic rainfall erosivity distribution (1951—1980)

The historic R factor follows the same gradient as annual precipitation, increasing greatly from the northwest to the southeast. The rainfall erosivity is minor for the third of China that receives less than 300 mm/year precipitation. The highest values are found on the Taiwan and Hainan islands where predicted R ranges from 1,000 to 2,000. The R values are found to be higher than 300 for most of the Yangtze River basin and areas south of the Yangtze. By comparison, the US R values range from 20 to 550. Northern China receives less rainfall and therefore has lower R values, ranging from 100 to 300. Combining the R map with a topographic map (DEM), a cursory check can identify that the middle-reaches of the Yellow and the middle- to upper-reaches of the Yangtze regions are most vulnerable to historic soil erosion.

Table 1 Digital databases used in modeling erosivity (R) and water availability (Q) across China

Database		Resolution (Spatial and temporal)	Purpose	Data source and references
Topography (Digital elevation model)		1 km	Topographic classification	http://www.ngdc.noaa.gov/
Historic	Precipitation	10 seconds, averaged monthly for the period 1951—1980	Model F, R, *AET*, Q	Chinese central meteorological office, 1984
	Temperature	10 seconds, averaged monthly for the period 1951—1980	Model *PET*, *AET*, Q	
	Landuse/land-cover	1 km, 1992	Model *AET*, Q	Loveland *et al.*, 2000. http://landcover.usgs.gov/
Predict-ed by GCM	Precipitation	2.5^{o} by 3.75^{o}, monthly for the period 1960—2099	Model future effects on F, R, *AET*, Q	HadCM3 SRES climate change scenario, Climate Impacts LINK Project, http://www.cru.uea.ac.uk/link/in-dex.htm
	Temperature	2.5^{o} by 3.75^{o}, monthly for the period 1960—2099		

4.2 Historic water availability (1951—1980)

As represented in the hydrologic model, annual water yield or water availability is controlled by precipitation, potential *ET*, landuse/landcover, and topography. As expected, highest historic water availability was found in Taiwan and southern China while northern China has much less water. In lieu of regional measured streamflow data, we compared simulated water yield with that predicted by the model by Liu (1986). Although our model predicted the spatial water yield patterns well and the values of the 32,911 cells were highly correlated with those from Liu's model (R^2=0.89, P<0.0001), our model under-predicted by 26%. However, the averaged runoff ratio predicted by this paper (0.25) was identical to that predicted by Liu's model. The differences were probably in part due to the fact the Liu's model does not consider landuse or *PET* effects on streamflow. More watershed scale and regional model validations are needed to generate the appropriate parameters for China.

4.3 Climate change scenarios

We divided the entire climate database into four periods: 1960—2000 resents the historic prediction or the baseline, while 2001—2030, 2031—2060, and 2061—2099 represent the short-term, middle-term and long-term future climate projections. We compared HadCM3 predictions (1961—1980) for both air temperature and precipitation patterns with actual historic 'measured' weather data from 1951 to 1980 to provide an assessment of the GCM predictions.

Compared to the baseline from 1960 t0 2000, averaged air temperature was predicted to increase unidirectionally, 0.5 ^{o}C to 1.5^{o}C, 1.4 ^{o}C to 3.3^{o}C, and 3.0 ^{o}C to 6.7^{o} degrees, for the three future time periods, respectively. Annual precipitation was expected to increase and decrease, changing from –6.7% to 38%, from –19.1% to 42%, and from –6.7% to 87.5% for the three periods, respectively. In general, regions north of the Yangtzee River is expected to have greater changes in climate (Fig. 1).

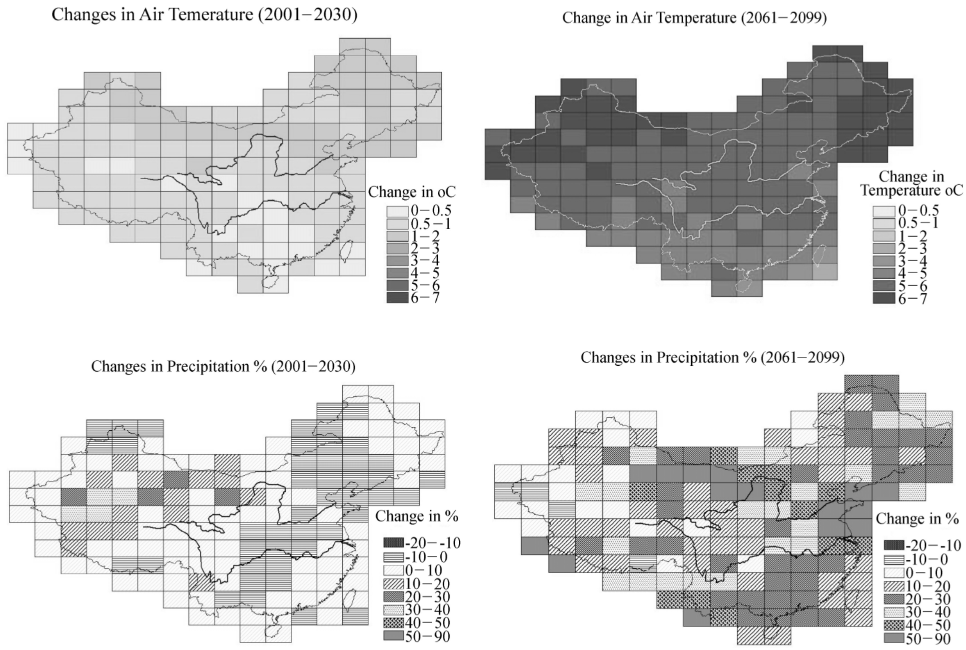

Fig.1 Climate change scenarios predicted by the HadCM3 SRES GCM

4.4 Effects of climate change on the rainfall erosivity (R Factor)

The R values were averaged for each of the periods and compared to the baseline (1960—2000) (Fig 2). During the following 30 years (2001—2030), with decreases in precipitation, erosivity in southeastern regions is expected to decrease, but overall average rainfall erosivity for the entire country is predicted to increase by 8.7% (–54% to 168%). This would be of special concern in northeastern China and the middle-reaches of the Yellow River basin. Following this relatively dry period, due to overall increase in precipitation in the next 60 years, R values are expected to increase greatly by 37% (–51% to 230%) and 93% (–50% to 861%) for the mid- and long-term periods, respectively. This means under the current landcover and land management conditions, soil erosion rates will increase by 37%—93% across China.

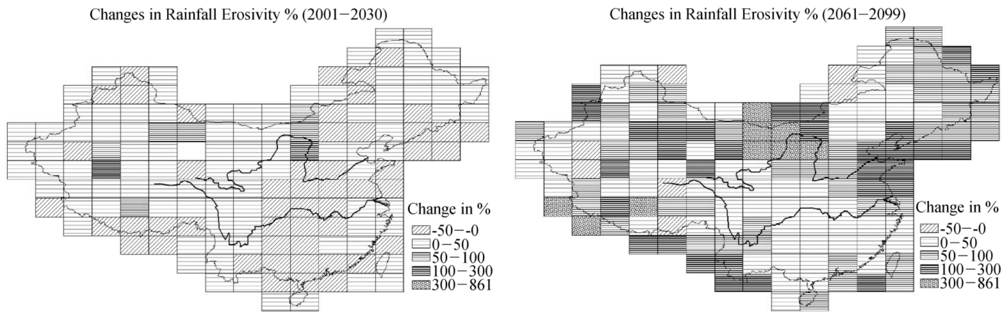

Fig. 2 Predicted changes in rainfall erosivity for the next 30 and 100 years

4.5 Effects of climate change on water availability

Water availability reflects the combined effects of changes in air temperature and precipitation. During the next 30 years, due to increases in air temperature and some decreases in precipitation, the majority of the eastern China, areas considered to be the ‘grain basket’, is expected to experience water resource reduction as high as 20% (Fig. 3). During the next 30 years, limited increases in water availability are expected in western China where water is most needed. Following this 30-year dry period, all of China is predicted to become wetter, especially in western Inner Mongolia, Shando, and Jiangsu provinces on the east coast. On average, 13.4% (–36.2% to 98.7%) and 20.9% (–28.1% to 198.6%) more water would be available during the second and the third periods, respectively.

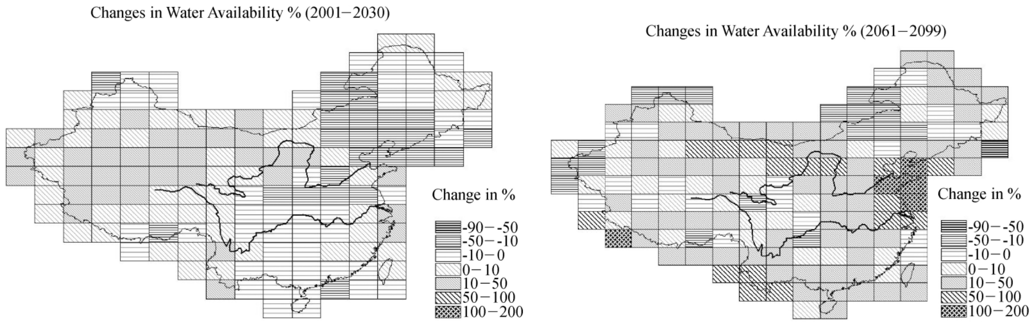

Fig. 3 Predicted changes in water availability for the next 30 and 100 years

5 Conclusions

Hydrologic and rainfall erosivity models were combined with a climate change model to assess the potential consequences of climate change on soil erosion and water resources across China. The climate change scenario predicts northern, eastern, and central China will experience a hotter and drier climate over the next 30 years. Significant reduction of available water was associated with this climate scenario. Rainfall erosivity is expected to significantly increase in northeastern and southeastern China in the next 30 years. From 2,061 to 2,099, both air temperature and precipitation are expected to increase greatly across China, and rainfall erosivity for soil erosion prone regions, the Yellow and Yangtze River basins and northeastern China, in particular, is expected to increase significantly. Soil erosion control continues to be a challenge China in the 21st century. Although more water may become available for most of China during the second half of this century, northern China is expected to experience more water stress due to a predicted high air temperature increases.

References

Deng, H. 2001. Impacts of climate change and landuse-landcover change on hydrology and water resources. Advance in Earth Sciences. 16(3):436-441.

Jiang, T., Y. Chen, J. Chen and X. Chen. 2000. Impact studies of future climate change on hydrological regimes and water resources in China. ACTA SCIENTIARUM NATURALIUM. UNIVERSITATIS SUNYATSENI. 39(2):151-157.

Liu, C. 1986. Analysis on water balance and research of water resources in China. Collection of Theses in the Third Hydrological Session of the Geography Society of China. Science Press, 113-118.

Liu, C. and G. FU. 1996. The impacts of climate warming on hydrological regimes in China: an overview. In. J.A.A. Jones *et al.*, (eds) regional Hydrological Response to Climate Change, 133-151.

Loveland, T.R., B.C. Reed, J.F. Brown, D.O. Ohlen, J. Zhu, L. Yang, and J.W. Merchant. 2000. Development of a Global Land Cover Characteristics Database and IGBP DISCover from 1-km AVHRR Data. International Journal of Remote Sensing, vol. 21, no. 6/7, p. 1,303-1,330.

Nearing, M.A. Potential changes in rainfall erosivity in the U.S. with climate change during the 21st century. J. Soil and Water Conservation, 56(3):229-232.

Qian, Z. and G. Zhang. 2001. Comprehensive Report on the Sustainable Development of China's Water Resources In: Research Reports on Sustainable Development on China's Water Resources, vol. 1. 3-32.

Renard, K.G. and J.R. Freid. 1994. Using monthly precipitation data to estimate the R factor in the revised USLE. J. of Hydrology. 157:287-306.

Shen, G. and L. Wang. 2001. Eco-Environmental Reconstruction and Water Resources Protection and Utilization in China. In: Research Reports on Sustainable Development on China's Water Resources, vol. 7.

Sun, G., J. Lu, D. Amatya, S. McNulty. 2002. Modeling climatic and forest management effects on annual water yield across the Southern US. In Proceedings of the 2nd Federal Interagency Hydrologic Modeling Conference. July 28 –August 1, 2002. Las Vegas, USA.

Zhang, L., W.R. Dawes, and G.R. Walker. 2001. Response of mean annual evapotranspiration to vegetation changes at catchment scale. Water Resour. Res., 37:701-708.