A multifactor analysis of the spatial distribution of annual mean extreme precipitation- Taking the Yellow River Basin as an example

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Abstract. Because the current interpolation method cannot meet the accuracy specifications, a new method for spatial interpolation of extreme precipitation is developed. It integrates precipitation, longitude and latitude, elevation, and topography data such as slope and aspect, and it is then simulated by the high accuracy surface modelling method and applied in the Yellow River Basin (YRB). Results show that the integrated method affords a very good simulation precision, with its simulation precision error being far below other interpolation methods. In conclusion, the integrated method for spatial interpolation of extreme precipitation can afford a good solution in topographically complex areas.

1. Introduction

The Special Report on Extreme Events (SREX) of the intergovernmental panel on climate change [1] emphasized potentially severe impacts from extreme precipitation. Characteristics of precipitation extremes are important in many practical applications [2]; they include time-domain, frequency domain, and spatial domain. Confirming the spatial domain is extremely important and practical, especially in extreme precipitation.

A large number of authors have studied extreme precipitation in many different regions all over the world. For example, Vahid Rahimpour Golroudbary and Yijian Zeng [3] have shown that the spatial distribution of extreme precipitation clearly reflects the regional differences in the Netherlands. Tao Gao and Lian Xie portrayed a similar result [4]: over the Yangtze River basin, spatiotemporal patterns of precipitation extremes is more uneven and unstable during the years 1981–2011. The spatial and temporal distributions of indices of precipitation extremes in Southeastern Tibet [5] are extremely irregular. The extreme precipitation studies in China [6] showed that the nonstationary GEV distributions performed better than their stationary equivalents. Long-term trends and variability of total and extreme precipitation in Thailand [7] indicate that large-scale climate phenomena in the Pacific Ocean are remote drivers of variability in Thailand's total and extreme precipitation. Elena Voskresenskaya and Elena Vyshkvarkova [8] have indicated that extreme precipitation throughout the Crimean peninsula increases during the winter season and decreases during the summer season. There were no obvious trends shown by the changes in extreme precipitation events in the Loess Plateau...
(China) during 1960–2013 under global warming [9]. It is found by Huiliang Wang et al [10] that extreme precipitation events over the Yellow Sea western coast make a wetted winter season.

However, most of the studies use traditional methods, such as inverse distance weighting model (IDW), triangle net model (TIN), krigagan model (Kriging), and spline interpolation module (Spline) to confirm the spatial domain of extreme precipitation. These current popular interpolation methods, are theoretical interpolation methods and are not based on physical truth, such as longitude and latitude, elevation, slope, and so on. Therefore, these methods do not have any physical significance and their interpolation results have a higher error. In fact, each of the above methods has theoretical problems. To solve this problem and improve the accuracy of extreme precipitation spatial distribution, the method of high accuracy surface modeling (HASM) is applied, which is based on the theory of differential geometry surface. Due to the spatial distribution of extreme precipitation being closely related to longitude and latitude, elevation, and slope, it would have a better performance and be closer to the actual distribution of extreme precipitation by taking all other influence factors into account when conducting spatial interpolation of precipitation.

2. Materials and methods

2.1. Study area

The Yellow River basin (YRB, figure 1) is situated in the subtropics with latitude between 32° and 42° N and longitude between 96° and 119° E, and a length and width at about 1900 km and 110 km, respectively. With a vast basin area, YRB stretches over Qinghai-Tibet Plateau, Inner Mongolian Plateau, Loess Plateau, and Huang-Huai-Hai Plain from west to east. Therefore, it has its own rules and characteristics under the background of climate change. The YRB is located in the arid and semi-arid climate zones; the west of YRB is drought and the east is wet with a drought spring and winter and rainy summer and autumn. Due to concentrated heavy rainfall, sparse vegetation, poor soil erosion resistance, and unreasonable human activities, Loess Plateau, one special landform in YRB, becomes one of the most serious soil erosion areas in China. The special topography Loess Plateau and the growing number of extreme weather events leads to an increasing ecological crisis, such as water loss, soil erosion, and land desertification. Therefore, it is extremely significant to study the temporal variations of extreme precipitation in YRB [9].

![Figure 1](image1.png)

**Figure 1.** Location of the Yellow River Basin and hydrometeorological stations over the Yellow River Basin.
2.2. Data sources
During 1961–2010, the National Climate Center (NCC) and China Meteorological Administration (CMA) provided daily precipitation dataset from 80 rain gauge stations. Figure 1 shows the distribution of the rain gauge in YRB. In order to guarantee the continuity and unity of all weather station data as much as possible, stations established after the year 1960 are eliminated and the stations whose data are continuous are selected. In the next place, all the data are passed through stringent quality control checks and error value correction.

As to the definition of extreme precipitation events, China Meteorological Administration (CMA) stipulates that the threshold value of extreme precipitation events is 50 mm daily precipitation. However, YRB has special geographical position and climate environment, so it is not accurate to take 50 mm daily precipitation as the threshold value of extreme precipitation events for arid and semi-arid regions in YRB. Based on the world meteorological organization, the international percentile calculation method is used as the threshold value of extreme precipitation events to overcome this deficiency. The exact approach to process precipitation data is: first, sort the daily precipitation data of the selected 80 stations from 1961—2010 in ascending order; second, take the value of the 95th percentile as the threshold value of extreme precipitation events.

2.3. Research methods
Longitude and latitude reflect the influence of the background of climate, circulation, and continentally to some extent. On the other hand, elevation reflects gradient effect of precipitation. Meanwhile, the aspect and slope of the local area in a certain extent represent the influence of prevailing wind-direction to precipitation. Therefore, to improve the space simulation accuracy of extreme precipitation events, longitude and latitude, elevation, aspect, and unobstructed terrain factors are taken into account.

- The coefficient equations of influence on precipitation slope

According to DEM data, the spatial analysis module of ARC/INFO extracts the 1 km grid slope data of YRB. In the extraction results, 0° is on behalf of due north direction, 90° represents due east, 180° represents due south, and 270° represents due west by turning it clockwise. From the view of precipitation distribution affected by the monsoon in YRB, the greatest influence is from the southeast and southwest monsoon, namely warm and wet flow from Pacific Ocean and Indian Ocean. Therefore, the influence of due south on precipitation defines the minimum value 1, and due north -1. Due to flat areas having no influences on precipitation, it is 0. The coefficient equations of slope and its influence on precipitation are performed as:

\[
\text{ASP}_{\text{index}} = -\cos \left( \frac{\pi}{(\text{Aspect} / 180)} \right) \quad \text{Aspect } \neq -1
\]

\[
\text{ASP}_{\text{index}} = 0 \quad \text{Aspect } = -1
\]

where \( \text{ASP}_{\text{index}} \) denotes the coefficient equations of slope and its influence on precipitation, \( \text{Aspect} \) are values of slope.

- The coefficient equations of influence on precipitation of terrain unobstructed factor

In addition to slope, the unobstructed terrain factor, in other words, the maximum elevation rate between one grid cell and the cell around it, has a significant effect on precipitation. The coefficient equation of influence on precipitation of t unobstructed terrain factor is given by:

\[
\text{V}_{\text{index}} = \left[ 1 + \cos \left( \pi \left( \text{Slope} / 180 \right) \right) \right] / 2
\]

Where \( \text{V}_{\text{index}} \) denotes terrain unobstructed factor; \( \text{Slope} \) is topographic slope.

- The regression equation of extreme precipitation and its influence factor

The precipitation data in YRB are time series from 1961 to 2010. Meteorological stations in YRB are all semi-automatic type, and there are regular calibrations and quality control. The calculation results show that the annual extreme precipitation of the dataset is accurate. It is necessary to further create a spatial model to improve the accuracy of precipitation simulation and analysis. Therefore, this study used DEM, longitude and latitude, elevation, aspect, and slope to establish the spatial model of extreme precipitation in YRB, and the establishment of the spatial model contains the following steps: first, use DEM data to calculate the DEM of YRB; second, calculate the aspect and slope of YRB; third, use longitude and latitude to establish the spatial distribution of precipitation events; fourth, use arid and semi-arid regions in YRB as sample spots to establish the spatial model.
Every station has precipitation, longitude and latitude, elevation and slope aspect and unobstructed terrain factor calculated by DEM. Annual mean extreme precipitation and its correlation factor have a good correlation. The regression equation is presented as follow:

\[ M_{pre} = 2659.733838 + 0.000176X_{cor} - 0.0004791Y_{cor} + 0.084694Z_{elevation} - 40.479061Asp_{index} - 107.599239V_{index} \]  

(3)

where \( M_{pre} \) is the fitted value of annual mean extreme precipitation; \( X_{cor} \), \( Y_{cor} \), \( Z_{elevation} \), \( Asp_{index} \) and \( V_{index} \) represent longitude, latitude, elevation, the coefficient of slope and terrain unobstructed factor, respectively.

The pre-treatment and modifier formulas of annual mean extreme precipitation in YRB can be established according to the above formula:

\[ M_{pre}(x, y) = M_{pre}(x, y) - 0.000176X_0(x, y) + 0.0004791Y_0(x, y) + 0.084694Z_0(x, y) + 40.479061Asp_0(x, y) + 107.599239V_0(x, y) \]  

(4)

\[ M_{pre}(x, y) = M_{pre}(x, y) - 0.000176X_0(x, y) + 0.0004791Y_0(x, y) - 0.084694Z_0(x, y) - 40.479061Asp_0(x, y) - 107.599239V_0(x, y) \]  

(5)

where \( M_{pre}(x, y) \), \( M_{pre}(x, y) \), \( X_0(x, y) \), \( Y_0(x, y) \), \( Z_0(x, y) \), \( Asp_0(x, y) \), \( V_0(x, y) \) are the pre-treatment values, annual mean extreme precipitation, longitude, latitude, elevation, the coefficient of slope, and unobstructed terrain factor of every station. \( M_{pre}(x, y) \), \( M_{pre}(x, y) \), \( X_0(x, y) \), \( Y_0(x, y) \), \( Z_0(x, y) \), \( Asp_0(x, y) \), \( V_0(x, y) \) and \( V_0(x, y) \) are the simulation values of every grid cell’s annual mean extreme precipitation, the pre-treatment of value of annual mean extreme precipitation, longitude, latitude, elevation, the coefficient of slope, and unobstructed terrain factor.

In the process of simulation, annual mean extreme precipitation of every station can be obtained by analyzing all the 80 stations in YRB, then the \( M_{pre}(x, y) \) of every station can be calculated according to the 4th formula and by using HASM for the interpolation. Finally, use the 4th formula to modify \( M_{pre}(x, y) \), the interpolation value.

3. Results

3.1. The accuracy comparison between the integrated method and other methods

In order to test the accuracy of the interpolation, 8 stations (10% of stations in YRB) are randomly extracted as authentication data, and the other stations (90% of stations in YRB) are interpolation stations. In this paper, four interpolation methods are used: IDW, Kriging, Spline, and HASM. Table 1 presents the statistical results of the different methods.

|               | Error of IDW (mm) | Error of Kriging (mm) | Error of Spline (mm) | Error of Integrated (mm) |
|---------------|-------------------|-----------------------|---------------------|------------------------|
| simulation    | 87.01             | 73.54                 | 137.22              | 8.88                   |

From table 1, annual mean extreme precipitation obtained with HASM from 1961 to 2010 with mean values shows very good simulation precision with a simulation precision error far lower than other interpolation methods. Spline has the maximum error. We can conclude that the integration of HASM and factors related to extreme precipitation such as longitude, latitude, elevation, the coefficient of slope, and unobstructed terrain factor display a good interpolation precision, and the
space analysis function and drawing function of ARC/INFO can perfectly reflect the interpolation results.

3.2. Spatial distribution of annual mean extreme precipitation in YRB
Spatial distribution of annual mean extreme precipitation in YRB is showed by figure 2.

![Figure 2. Spatial distribution of annual mean extreme precipitation in YRB.](image)

From figure 2, we can see that the maximum annual mean extreme precipitation is located in the east and southeast parts, and it can be as much as for 280 to 400 mm in one day. The amount of mean annual extreme precipitation in the YRB middle area is from 140 to 280, and the minimum distribute in the northwest part of YRB spreads from 51 to 140.

4. Conclusions and discussions
Because the current interpolation method cannot meet the accuracy specifications, a new method for spatial interpolation of extreme precipitation is developed. It integrates precipitation, longitude and latitude, elevation, and topography data such as slope and aspect. It is then by the high accuracy surface modelling method. The new approach for spatial interpolation of extreme precipitation can greatly improve the accuracy specification.

The YRB is a specific area in China as it stretches over different regions and the spatial distribution of extreme precipitation in it is very important for society, the environment, and the economy. There is a drastic difference in the precipitation in YRB from region to region, and from southeast to northwest the extreme precipitation progressively decreases. This is related to longitude, latitude, elevation, slope, and aspect. The new method for spatial interpolation of extreme precipitation in topographically complex areas such as YRB is a good solution.

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