Spatiotemporal precipitation variability and potential drivers during 1961–2015 over the Yellow River Basin, China

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Introduction

Precipitation is a key component of the hydrological cycle and affects agricultural systems, ecological changes and economic development across numerous regions. The Yellow River, known as the ‘Mother River of China’, is the sixth longest river in the world and the second longest in China and is of crucial importance to the country. In the Yellow River Basin (YRB), an arid and semi-arid region, precipitation is usually, but not always, greater than actual evapotranspiration. Water is an important limiting resource in this region not only due to its scarcity, but also its intermittent and unpredictable availability (Rodríguezturibe and Porporato, 2005). The spatiotemporal patterns and variation of precipitation directly affects the development and use of sustainable water resources. Environmental drivers accelerate the uneven distribution of water resources and water scarcity in the YRB, via changing precipitation patterns and decreasing runoff. Climate variability combined with human-induced greenhouse gas emissions has resulted in an increase in mean global temperature (IPCC, 2001), which is assumed to cause higher evaporation rates and, as a result, lead to greater amounts of water vapour in the atmosphere. The global hydrological cycle has been accelerated (e.g. Menzel and Bürger, 2002) and precipitation patterns may have changed. To address such issues, policy-makers require a clear understanding of the current situation. It is therefore essential to study the spatial and temporal variability of precipitation in relation to climate change and anthropogenic activities.

Previous studies have examined the trends in spatial and temporal variability of precipitation over the YRB using observations from rain gauges (Fu et al., 2004; Liu et al., 2008; Chang et al., 2014). However, as a climatic phenomenon that varies over space and time, precipitation would be better analysed by linking spatial and temporal changes. Data from rain gauges are a relatively good representation at the scale of individual stations, but not very effective at the areal scale due to their uneven spatial distribution (Xiao et al., 2016). For studies which intend to model distribution, such as flood forecasting and warning, water resource planning and climate change impact assessments, areal and gridded data are required. The acquisition of gridded precipitation data for locations across China has therefore been an important recent objective for the National Meteorological Information Center and China Meteorological Administration (Liao et al., 2017). This study makes use of interpolation grids that incorporate data from all rain gauges operated by the National Meteorological Information Center and the China Meteorological Administration, which is a novel and more representative way of measuring spatial and temporal variation in precipitation over the entire YRB. In addition, new records from the last decade, in which significant variation in precipitation patterns is evident, have been imported for the reanalysis of precipitation patterns.

The 400mm isohyet is a very important geographical marker in China and is largely identical to the Hu Line (Heihe–Tengchong Line, or Aihui–Tengchong Line). It marks the boundary between semi-arid and semi-humid regions, forest and grassland cover, agricultural and nomadic civilisations, and monsoon and non-monsoon regions. The isohyet roughly divides China into two parts: southeast and northwest. Approximately 90% of the farmland and population is located to the east of the line. A shift in its location would have a significant impact on fields as diverse as geography, environmental science, resource science, agricultural science, economics and sociology (Wang et al., 2005). The line passes through the upper and middle reaches of the YRB. It is important to identify any changes in the location of the 400mm isohyet over the YRB.

The objectives of this paper are as follows: (1) to investigate the spatial and temporal distribution of multi-timescale precipitation for the period 1961–2015 using interpolated grid data, rather than rain gauge observations; (2) to explore trends in the data and their spatial distribution; (3) to analyse variations in the location of the 400mm isohyet using updated precipitation data and identify the potential drivers. This study focuses on identifying changes in precipitation patterns over the YRB under changing environmental conditions, in terms of both climate change and surface-level changes resulting from human activities.

Data and methodology

The Yellow River Basin study area

According to survey results from 1973, the Yellow River is 5464km long, with a basin area of 752 443km2. The watershed area is as large as 794 712km2 if the Erdos inner flow area is included. According to statistical data from 1997 (Yellow River Commission, 1999), there were 107 million residents and 12.6 million hectares of cultivated land within the watershed, representing 8.6% and 13.3% of the national totals, respectively.

The Yellow River flows through arid, semi-arid and semi-humid regions. It is well known for its history and its large drainage area, as well as its high sand content, frequent floods, unique channel characteristics in the lower reaches (the riverbed is higher than the land outside the banks), and limited water resources (Fu et al., 2004). The drainage basin area accounts for 8% of the total area of China, yet runoff from the basin accounts for only 2% of the national total. The per capita distribution of water...
resources in the watershed is only 25% of the average for China and 6.25% of the global average. Both spatial and temporal precipitation variability have affected water security in the YRB – with consequences for water supply, agriculture and eco-system processes – and there is good evidence that global warming is one of the factors which influences these changing precipitation patterns. A greater number of zero-flow days have occurred at the mouth of the Yellow River in recent years (Liu and Cheng, 2000; Liu, 2004). McVicar et al. (2002) asserted that a decrease in precipitation alongside increases in agricultural and industrial water use are the main causes of the decrease in runoff and the drying observed in the YRB. Temporal and spatial precipitation patterns have been evaluated for the upper reaches of the Yellow River (Yang and Li, 2004; Shao et al., 2006; Chang et al., 2014). Liu et al. (2008) showed a decreasing trend in precipitation at most of the 81 meteorological stations analysed for the period 1961–2006, with only two meteorological stations in the YRB displaying an upward trend; similar results were obtained by Chang et al. (2014) using data from 143 rain gauges collected from 1961 to 2010.

However, according to our literature review, few studies have tested the spatial distribution of precipitation trends using grid-based data from a sufficiently large number of stations or explored the effects of climate change, especially in terms of the regional response over the last decade. In this study, a high-resolution (0.25°×0.25°) precipitation data series is used to investigate temporal trends in precipitation over the last 55 years, based on records for 4747 grids (Xu et al., 2009; Wu et al., 2013); analysis of the spatial distribution of precipitation trends over the YRB is also presented. To explore the changes in the precipitation patterns over the region, data for the second-grade districts – as first proposed by the China Renewable Energy Engineering Institute and widely employed in the study of river basins in China – were used. Figure 1 shows the location of the YRB in China and the boundaries of the second-grade water resource districts.

**Methodology**

**Trends and abrupt change points**

The non-parametric Mann–Kendall (M–K) trend test, as established by Mann (1945) and further developed by Kendall (1975), was employed to detect the presence of abrupt changes and/or trends. The main advantage of this test is that it can provide predictive power that is nearly as high as its parametric competitors without any assumptions about the distribution of the data. The M–K method can identify more significant trends, particularly when applied to annual total precipitation data (Serrano et al., 1999), and it has been highly recommended for general use by the World Meteorological Organization (Mitchell et al., 1966). The M–K test has been widely used as an effective method of evaluating trends and abrupt change points in hydrological and climatological time series (Herath et al., 2018). It is based on the following assumptions: that the time series data represent the true conditions, that in the absence of a trend the data are independently and identically distributed, and that the data collection methods are unbiased.

The M–K test does not require the data to be normally distributed. A null hypothesis of no trend is used, which will be rejected if the p-value is less than the significance level α. The forward trend statistic, UF, is calculated using the time series data, while the backward trend statistic, UB, is calculated using the reversed time series (i.e. from the end of the time series to the beginning). If UF exceeds the upper or lower confidence limit, then it can be concluded that the series has an increasing or decreasing trend, respectively. A typical confidence level of 95% (i.e. a significance level of 0.05) was used for the derivation of the confidence limits. If UF and UB intersect between the two confidence limits, an abrupt change point is identified at the point of intersection (Yang and Tian, 2009).

**The stability of trends**

The Hurst exponent (Hurst, 1951) has been applied in many research fields since it was first proposed. It provides a measure for the long-term memory and fractality of a time series dataset. Due to its robustness, with few assumptions about the underlying system, it has broad applicability for time series analysis (Mielińczuk et al., 2007). The values of the Hurst exponent (H) range between 0 and 1. Based on the value of H, time series can be classified according to three categories: (1) $H = 0.5$ indicates a random series; (2) $0 < H < 0.5$ indicates an anti-persistent series; and (3) $0.5 < H < 1$ indicates a persistent series. The Hurst exponent can be used to predict whether trends will continue or reverse – or are simply random – by evaluating the self-similarity and long-range dependence of a series. In this study, the traditional expression of the Hurst exponent R/S (rescaled range statistic) estimator was used to assess precipitation trends.

**Isohyet extraction and spatial location definition**

Based on the gridded annual precipitation data, a contour can be generated using the ‘Spatial Analyst Tools’ tool built into ArcGIS (a geographical information system), by following the steps below: (1) generate the rainfall vector points according to the coordinates of the rain gauges used for each year; (2) using a spatial interpolation method such as Kriging, generate the precipitation for an areal grid, using a Yellow River mask to extract the isohyets; (3) create the isohyets using the interpolated grid. The ‘contour interval’ parameter can be set as an integer in order to easily find the 400mm contours; here the interval was set at 50. The 400mm isohyet was selected by setting ‘contour=400’ in the programme.

Kriging interpolation is a key process in the derivation of the interpolated grid and isohyets. It is a geostatistical method which fits a mathematical function to a specified number of points, or to all points within a specified radius, to determine the output value for each location. It is most appropriate when there is a spatially correlated distance or directional bias in the data, as is often found in geological data.
Thus, it was employed here for the analysis of the spatial characteristics of variations in precipitation. The general formula represents a weighted sum of the measured data:

\[ \hat{Z}(s_0) = \sum_{i=1}^{N} w_i Z(s_i) \]

where \(Z(s_i)\) is the measured value at the \(i\)th location, \(w_i\) is an unknown weight for the measured value at the \(i\)th location, \(s_0\) is the prediction location and \(N\) is the number of measured values. The weight \(w_i\) depends not only on the distance between the measured points and the prediction location but also on the overall spatial arrangement of the measured points, which can be derived by fitting a mathematical function to the data (using a semivariogram model). The semivariogram model can be circular, spherical, exponential, gaussian or linear. The exponential model – which is commonly used – was chosen for this study.

The 400mm isohyets could consist of several discrete fragments and may exhibit a fractal spatial distribution. The initial contours were therefore further processed by carrying out the following sequence: the longest arc is defined first; shorter arcs that cannot be used to represent the contour are removed; continuous arcs and the contours with wider latitudinal ranges are selected; and, finally, the scattered isolines without any connections with other arcs are excluded (Figure 2). Some aspects of the arc selection process, especially with respect to the discrete parts, may be prone to subjective differences.

The selection of interpolation model when using the Kriging method, as well as the treatment of discontinuities when processing the contours, will cause slight differences in the construction of isohyets. However, these potential biases will be the same for each decade and so they should not affect the analysis of the 400mm isohyet shifts.

This study used the weighted average location of a contour to characterise its spatial position. The ‘Feature Vertices to Points’ tool in ‘ArcToolbox’ was used to disperse the 400mm contour into points, and the weighted average location was deduced from latitude/longitude coordinates. The weighted average of the spatial variation of an annual precipitation contour (e.g. the geographic centre of the isohyets) was used as a measure of the spatial shift of precipitation.

Results and discussion

Annual precipitation trends

Figure 3 shows the spatial distribution of the average annual precipitation in the YRB from 1961 to 2015, which is lower than 800mmyear\(^{-1}\) over most of the basin. Only small regions in the southern and eastern parts of the YRB had values higher than 800mmyear\(^{-1}\). The pattern of precipitation is very uneven; both arid and semi-arid climate conditions are experienced in the region. The water supply of the YRB is subjected to heavy demands as a result of socio-economic development in the region, especially as it flows through the Loess Plateau, an ecologically fragile area in North China. According to the findings of the M–K trend test presented in Figure 4, no trend in precipitation was identified (according to the UF statistic); however, an intersection point between the two lines, corresponding to 2012, can be seen. Thus, 2012 could initially be considered to be an abrupt change point. To explore spatial variations in the pattern of precipitation distribution, M–K trend analysis was performed for each grid. Figure 5 indicates that precipitation in the upper parts of the basin ((1) above Longyang Gorge, (2) Longyang Gorge to Lanzhou and (6) Hekou Town to Longmen) has increased, and in the southern parts ((1) above Longyang Gorge and (2) Longyang Gorge to Lanzhou) and eastern parts ((5) Longmen to SanMenXia and (7) SanMenXia to HuaYuanKou) has decreased, which might affect runoff generation. Most
that occurred before and after 1990. The period 1961–1990 was chosen as the baseline period. By comparing the annual precipitation data for the period 1991–2015 with the data for 1961–1990 (Figure 6), a similar trend to that shown in Figure 5 was identified, with increasing precipitation trends found for locations in the upper reaches and decreasing trends found for the southern reaches of the basin, as well as a slight increase in the western and northern parts in the precipitation anomaly data.

### 400mm Isohyet Variation

Figure 7 shows variations in the location of the 400mm isohyet for different decades over the YRB. Generally, a shift of the isohyet towards the north and west is observed across the decades, though the opposite was observed for the period 1991–2000. Then the shift has been kept after 2000 and particularly 2010. In contrast to the above, a previous study (Wang et al., 2005) found that the 400mm contours have generally moved towards the south and east from 1956 to 2000. This highlights the importance of using up-to-date data – analysis conducted using older data for the study area yields results which are in direct opposition to those calculated here. The direction of movement presented in this study is consistent with a more recent study of the 400mm isohyet across China (Yuan et al., 2014). This result demonstrates that the precipitation pattern has changed, thereby affecting the distribution of water resources in the YRB.

### Table 1

| Time series | H(longitude) | H(latitude) |
|-------------|--------------|-------------|
| 1961–2000   | 0.63         | 0.54        |
| 1961–2015   | 0.52         | 0.64        |
Displacement of the geographic centre of the isohyets could reflect the movement of the line. Figure 8 shows the shifts in the centre point of the 400mm isohyet in terms of longitude and latitude for the time series covering the whole 1961–2015 period; the periods 1961–2000 and post-2000 are shown in blue and black, respectively, for the purpose of comparison. Based on the black dashed trend lines for 1961–2000 shown in Figures 8(a) and 8(b), it might be concluded that the isohyet shifted to the east and south. However, consideration of the entire time series from 1961 to 2015 reveals that the eastward trend is weakening (black solid trend line in Figure 8(a)), while a shift in latitude to the south appears to cease (Figure 8(b)). The values of the Hurst exponents support a similar conclusion (Table 1). The Hurst exponent for longitude was 0.63 for the period 1961–2000, suggesting a sustained state; however, the value reduces to 0.52 when the time series is extended to 2015, suggesting a random series. This explains why the longitudinal trends are different for the two time series. The exponents for latitude vary between values indicating a random series (0.54) to those indicating the maintenance of the current state (0.64), which indicates a weak increase in precipitation to the north. The results support the idea that the overall trend is for a shift towards the north and west for the whole series from 1961 to 2015.

**Summer and extreme precipitation trends**

The precipitation over the YRB is uneven across the year and is concentrated mainly into the summer period – 70% of annual rainfall occurs between June and September with the midsummer period of July to August accounting for 40%. In addition to knowledge of the general climate characteristics of the YRB – i.e. wet summer and autumn; dry winter and spring – it is important to identify any summer precipitation trends.

No significant trends were found for the summer precipitation time series over most parts of the YRB (Figure 9). However, significant increasing trends were detected in the western part of the basin ((1) above Longyang Gorge) and for several grids in the region of Hekou Town to Longmen District (6), while some southern grids ((2) Longyang Gorge to Lanzhou) showed a decline. No significant changes were observed for the summer precipitation over the whole basin and data for the annual precipitation series over the study area – barring a few grids – are presented in Figure 5.

To explain the summer precipitation trends, analysis of the daily extreme precipitation distribution data is presented in Figure 10. The diagram shows the location at which each year's rainfall extreme was observed; the data points demonstrate that the geographical centres of extreme precipitation shifted towards the north and west from 1991 to 2015, relative to the 1961 to 1990 observations. According to the results of the Mann–Kendall test (Figure 11) the change in extreme precipitation levels was unremarkable.

**Potential drivers of the 400mm isohyet shifts**

Spatiotemporal variations in precipitation over the YRB, especially the movement of the 400mm isohyet and extreme daily rainfall events, could be exacerbated by environmental changes, including changes...
in climate and at surface level. The East Asian Monsoon has a notable influence on precipitation over China, as well as over the YRB. The East Asian Summer Monsoon (EASMI) is itself affected by the North Atlantic Oscillation (NAO), the Indian Ocean Dipole (IOD) and the Pacific Decadal Oscillation (PDO; Xiao et al., 2015). The El Niño-Southern Oscillation (ENSO) has been recognised as a dominant driver of summer precipitation (the rainy season) in China (Cao et al., 2017).

These climate indices were therefore studied in an attempt to ascertain their potential effects on the isohyet shifts. In general, no significant trends or abrupt changes were found for these indices. The precipitation trends discussed above were not identified for the year 2000 (the year during which there was a shift in the location of the 400mm isohyet), or in 2012 (when there was a potential abrupt change point for annual precipitation over the whole basin) in the climate index data. This could be due to the nature of the annual average precipitation timescale, at which direct effects of extreme climate/weather events due to climate change are not evident, in contrast to daily precipitation extremes (Mishra et al., 2018). Table 2 provides the Pearson correlation coefficients for annual precipitation versus various climate indices. ENSO shows a more marked correlation than other climate indices and the correlation coefficients associated with ENSMI and NAO appear to exhibit some variation between the two different periods. However, no definitive variation was observed for any of the climate indices. Hence, it can be concluded that these climate factors cannot be the main driver of the 400mm isohyet shifts.

Due to large-scale soil and water conservation measures that have been implemented in the YRB, the vegetation cover has improved. He et al. (2017) demonstrated that around 60% of the YRB has seen improvements in vegetation coverage and that the trend will continue. No change has been observed over the remaining 40%. Overall, the vegetation coverage has increased significantly over the YRB. Figure 12 shows the variations in Leaf Area Index values before and after 2000 – a remarkable improvement in vegetation cover is evident, especially in the middle reaches of the YRB. Coupled with global warming and the regional temperature increase (Zhang et al., 2013), the vegetation increase should speed up the evaporation process and may facilitate the movement of increased precipitation to the western part of the basin. The vegetation and precipitation over the region therefore comprise a two-part system in which each component drives the other. Good vegetation cover can improve water conservation and provide water vapour for the generation of rainfall via evaporation and transpiration. In turn, increased precipitation directly promotes an increase in the extent of vegetation cover. The improvements in vegetation coverage could therefore be the dominant driver of the reverse shift observed in the 400mm isohyet, relative to the data recorded in an earlier study by Wang et al. (2005), which evaluated precipitation until 2000.

**Summary**

The results presented here indicate that marked changes in precipitation patterns have been observed for the last decade over the study area. Though no overall significant overall trend in annual precipitation was detected over the YRB, a declining trend was found for the southern part...
of the basin and an increasing trend was shown for some areas of the western and northern parts of the basin. It is worth noting that the 400mm isohyet has shifted significantly to the north and west, rather than to the east and south, as suggested by a previous study of data for the period 1956–2000 (Wang et al., 2005); variation in the distribution of extreme precipitation events indicates a similar tendency. The values of the Hurst exponents indicated a random series of longitudinal shifts and static latitudinal locations. Shifts in the isohyet location were maintained within a certain range of movement, but a very significant shift was observed after the year 2010. The year 2012 was identified as an abrupt change point, and as such it is critical that more attention is given to new records as they become available in the future, to facilitate effective water resource management, environment reconstruction and sustainable development planning.

The changes in precipitation patterns might have been influenced by both climate change and changes occurring at surface level. Climate indices such as the EASMI, NAO, IOD, PDO and ENSO were examined to establish the extent to which they might have influenced changes in precipitation over the YRB, but no significant reverse tendency was observed during the decades before or after the year 2000. However, the vegetation coverage across the YRB – a dominant component of surface-level change – has improved significantly over the last few decades, following the implementation of large-scale water conservation and soil conservation. Improved vegetation coverage and increased regional precipitation over the Yellow River Basin, but no significant shift was observed after the year 2010. The year 2012 was identified as an abrupt change point, and as such it is critical that more attention is given to new records as they become available in the future, to facilitate effective water resource management, environment reconstruction and sustainable development planning.

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