Temporal variations of runoff in a rapidly urbanizing semi-arid Chinese watershed
Ruizhong Gao, Fengling Li, Xixi Wang, Tingxi Liu and Dandan Du

ABSTRACT
Rapid urbanization on streamflows may directly affect or be restricted by the sustainability of local water resources. This is particularly true for arid/semiarid areas such as the Wulanmulun River watershed in the rapidly-developing Ordos region of north central China. From 1997 to 2012, the gross domestic product (GDP) of the region increased fifty-fold, while the urban area grew by a factor of ten. This study fused multiple-source data on land use, hydrometeorology, and socioeconomics to examine temporal variations in the runoff due to climate change and urbanization. The results revealed that for the Wulanmulun River watershed, the runoff decreased consistently over the study period, with an inflection point around 2005. The average runoff from 2006 to 2012 was much smaller than that from 1997 to 2005, regardless of time scale; although the precipitation also fluctuated from 1997 to 2012, it exhibited no significant trend. From 1997–2005 to 2006–2012, both the urbanized area and GDP increased eight-fold while the population increased by 20%. Thus, urbanization rather than climate change is likely the major reason for the decrease in runoff after 2005. For the study watershed, low impact development practices (e.g. rain barrels) may need to be implemented during urbanization to achieve sustainable management of water resources.

INTRODUCTION
In areas that are experiencing rapid urbanization such as the Wulanmulun River watershed in north central China, temporal trends in the streamflow can provide a useful indicator of whether this development is sustainable in terms of the available water resources (Park et al. 2013; ScienceDaily 2014). Urbanization reduces infiltration and thus tends to increase storm flow volume, peak discharge, frequency of floods, and surface runoff (Paul & Meyer 2001; Jennings & Jarnagin 2002; Smith et al. 2005; Dougherty et al. 2006; Scalenghe & Marsan 2009; Erickson & Stefan 2009; Mejia & Moglen 2010; Ogden et al. 2011; Du et al. 2012; Verbeiren et al. 2013). However, the observed runoff streamflow at the outlet of a watershed (hereinafter simply referred to as ‘runoff’ for convenience), which is computed as the ratio of observed total streamflow at the outlet to the drainage area of the watershed, may actually decrease because urbanization can also result in increased water consumption for socioeconomic development as well as food and energy production. Such a downward trend in the runoff may indicate that urbanization has been negatively impacting the availability of water resources, limiting the long-term sustainable development of the area (Du et al. 2012; Miller et al. 2014).

Extensive efforts have been made to examine how urbanization affects watershed hydrologic processes. For example, Valeo & Moin (2000) used the TOPMODEL model to predict possible changes in hydrologic components in urbanizing watersheds in the USA, while Cheng & Wang (2002) utilized meteorological data to define the change in degree of runoff hydrographs in urbanizing basins. White & Greer (2006) took a different
approach, looking at the potential effects of watershed urbanization on runoff and riparian vegetation in a coastal watershed in California. Huang et al. (2008) applied a regression method to analyze the effects of growing watershed imperviousness on streamflow timing and peak of the urbanizing Wu-Tu watershed in Taiwan; Franczyk & Chang (2009) used the semi-distributed ArcView Soil and Water Assessment Tool hydrologic model to assess the effects of climate change and urbanization on runoff in the Rock Creek basin in the Portland, Oregon, metropolitan area; and Lin et al. (2009) assessed the impact of land-use patterns on runoff by developing and comparing optimal and empirical models for the development of an urbanized watershed forest in Taiwan. Im et al. (2009) assessed the impact of urbanization on hydrology in the Gyeongancheon watershed of Korea using MIKE SHE, a physically-based watershed model, while Chu et al. (2010) modeled the hydrologic effects of dynamic land use change using a distributed hydrologic model (DHSVM) and a spatial land use allocation model (CLUE-s), also in the Wu-Tu watershed. Du et al. (2012) assessed the effects of urbanization on annual runoff and flood peak using an integrated hydrological modeling system (HEC-HMS) for the Qinhai River basin of China; Verbeiren et al. (2015) assessed the effect of urbanization on the rainfall–runoff relationship using the physically-based runoff model WetSpa in conjunction with remote sensing data; and Chu et al. (2015) quantified the potential effects of varying degrees of urbanization on the frequency of discharge, velocity, and water depth using MIKE SHE and MIKE-11, a 1-D hydrodynamic river model. All of these studies rely heavily on computer models to predict the effects of urbanization on hydrology, but as all the computer models require detailed data that may not be available for many watersheds, including the Wulanmulun River watershed, their applications are limited in practice and may be subject to various unreasonable assumptions.

The objective of this study was, therefore, to use an alternative approach to fuse multiple-source data layers of land use, hydrometeorology, and socioeconomics to examine how runoff temporal variations at different time scales are affected by urbanization in the Wulanmulun River watershed. This new approach consists of data exploratory analysis, the modified Mann–Kendall method, and principal component (PC) analysis.

**STUDY AREA**

The 1,950 km² upper section of the Wulanmulun River watershed (109°25′–110°11′E longitude, 39°19′–39°53′N latitude), located in the semiarid Ordos region of north central China (Figure 1), was selected for this study because it is a typical rapidly-urbanizing watershed with a dry climate and the river is a major water source for the entire Ordos region. The local economy is mainly dependent on coal mining and has rich mineral deposits. This type of economy is very sensitive to water resource availability and cannot be sustained without a stable and sufficient water supply. Ordos is one of the rapidly-developing regions in China; between 1997 and 2012 the gross domestic product (GDP) and urbanized area increased approximately fifty-fold and ten-fold, respectively. If this rate of growth is to be sustainable, it is crucial to determine whether an adequate water supply will be available from the study watershed by examining any changes in the runoff that have occurred as a result of this rapid development.

The watershed has a topographic elevation ranging from 905 to 1,627 m above mean sea level. Its land cover consists of urban areas, grass, forest, crops, water and fallow land. The main soil types are sandy loam, chestnut, sandy, and loess. The watershed receives an average of 358 mm precipitation annually, with the majority falling in the rainy season from May to September. It has a mean annual evaporation of 1,390 mm and a mean annual temperature of 7.3 °C.

**MATERIALS AND METHODOLOGY**

**Data and pre-processing**

Data on hydrometeorology, land use, and socioeconomics were utilized in this study. Daily data on hydrometeorologic parameters, namely streamflow, precipitation, evaporation, wind speed, sunshine duration, air temperature, and relative humidity, were collected at the flow station located at the outlet of the watershed, five rain gauge stations and two...
climate stations (Figure 1 and Table 1) by the National Hydrology Bureau and Metrology Bureau of China. The daily streamflow was divided by the watershed drainage area to calculate the runoff; the daily values of runoff, precipitation and evaporation were summed to obtain the monthly values, which in turn were summed to give the seasonal and annual values. Daily values for wind speed, sunshine duration, air temperature and relative humidity were arithmetically averaged to obtain the monthly values, which in turn were arithmetically averaged to give the seasonal and annual values. The 1997–2012 annual data on socioeconomic indexes, namely population, GDP, primary-industry product (PIP), secondary-industry product (SIP), tertiary-industry product (TIP), and construction-industry product (CIP), were obtained from the statistical yearbooks published by local government agencies for the region’s two major urban centers, Dongsheng District and Ejin Horo Banner (www.cnki.net). A detailed topographic map of the

Table 1 | Hydrometeorological stations where data were used in this study

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Longitude (degree)</th>
<th>Latitude (degree)</th>
<th>Altitude (m)</th>
<th>Record period</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zhuanlongwan</td>
<td>Flow</td>
<td>110.02</td>
<td>39.52</td>
<td>1,192</td>
<td>1996–2012</td>
<td>Flow, precipitation</td>
</tr>
<tr>
<td>Zaotuhao</td>
<td>Rain</td>
<td>109.95</td>
<td>39.67</td>
<td>1,303</td>
<td>1996–2012</td>
<td>Precipitation</td>
</tr>
<tr>
<td>Hetongmiao</td>
<td>Rain</td>
<td>109.52</td>
<td>39.65</td>
<td>1,453</td>
<td>1996–2012</td>
<td>Precipitation</td>
</tr>
<tr>
<td>Duoziliang</td>
<td>Rain</td>
<td>109.55</td>
<td>39.75</td>
<td>1,507</td>
<td>1996–2012</td>
<td>Precipitation</td>
</tr>
<tr>
<td>Hantaimiao</td>
<td>Rain</td>
<td>109.82</td>
<td>39.83</td>
<td>1,467</td>
<td>1996–2012</td>
<td>Precipitation</td>
</tr>
<tr>
<td>Yijinhoro</td>
<td>Climate</td>
<td>109.73</td>
<td>39.57</td>
<td>1,320</td>
<td>1996–2012</td>
<td>Precipitation, evaporation, wind speed, sunshine duration, air temperature, relative humidity</td>
</tr>
<tr>
<td>Dongsheng</td>
<td>Climate</td>
<td>109.98</td>
<td>39.83</td>
<td>1,427</td>
<td>1996–2012</td>
<td>Precipitation, evaporation, wind speed, sunshine duration, air temperature, relative humidity</td>
</tr>
</tbody>
</table>
area in the form of a 30-m digital elevation model (DEM) was downloaded from the Geospatial Data Cloud website (www.gscloud.cn) and used to delineate the boundaries of the watershed and its subwatersheds and streams.

The data on land use were derived from the Landsat Thematic Mapper (TM) images for 1997, 2000, 2005, and 2011, downloaded from the US Geological Survey (USGS) website (http://glovis.usgs.gov). The downloaded TM images were preprocessed using the image analysis tool of ArcGIS® 10.1 for band combination, radiometric enhancement, spatial enhancement, spectral enhancement, and projection to the Universal Transverse Mercator coordinate system, after enhancement, spectral enhancement, and projection to the

data on land use were derived from the Landsat Thematic Mapper (TM) images for 1997, 2000, 2005, and 2011, downloaded from the US Geological Survey (USGS) website (http://glovis.usgs.gov). The downloaded TM images were preprocessed using the image analysis tool of ArcGIS® 10.1 for band combination, radiometric enhancement, spatial enhancement, spectral enhancement, and projection to the Universal Transverse Mercator coordinate system, after which the preprocessed images were overlaid with the DEM and then resampled to have a spatial resolution of 30 m. The resampled images were then further processed using the supervised classification function of ArcGIS® 10.1 to derive land use maps for the years 1997, 2000, 2005, and 2011. In terms of the ground truth, the land use maps have four categories: urban, water, vegetation, and fallow. Finally, the derived land use maps were visually compared with the Google® Earth map for validation and any discrepancies resolved.

Examination of precipitation-runoff relationship

At annual, seasonal, and monthly time scales, visualization plots showing precipitation and runoff versus time were visually examined to identify temporal variations and/or trends. Scatter plots showing time-interval runoff versus time-interval precipitation, and a double mass curve (DMC) showing cumulative runoff versus cumulative precipitation, were used to determine whether the precipitation-runoff relationship was consistent throughout the entire analysis period. The DMC has been widely used in practice because of its simplicity; previous studies (Xu et al. 2003; Sun et al. 2007; Gao et al. 2011) successfully used a DMC to detect the effects of land use/cover changes on runoff. An inflection point in a DMC can be interpreted as a demarcation point at which the precipitation-runoff relation altered, because the slope of the DMC for natural conditions should be nearly constant. The sudden slope change around the inflection point can thus be attributed to changes in watershed characteristics (e.g. urbanization) and/or the climate. The runoff coefficient, the ratio of runoff at the watershed outlet to areal total precipitation, was computed to further verify whether the precipitation-runoff relation had indeed altered. Because runoff coefficient represents the percentage of precipitation that can be converted into runoff and reflects the combined effects of interception, storage, infiltration, and evapotranspiration on runoff, sudden changes can indicate alterations to the original precipitation-runoff relationship.

Trend detection

The Mann–Kendall test technique (Mann 1945; Kendall 1970) is widely used to detect trends in hydrometeorological time series (Zhang et al. 2004; Partal & Kahya 2006; Modares & Silva 2007; McBean & Motiee 2008; Basistha et al. 2009; Rai et al. 2010; Tabari et al. 2011; Some’e et al. 2012; Pingale et al. 2014; Sayemuzzaman et al. 2014). It assumes that the time series of interest is serially independent (von Storch & Navarra 1995; Yue & Wang 2002; Sayemuzzaman et al. 2014). A positive correlation in the time series increases the likelihood of significance, and could thus indicate a non-existent trend (Cox & Stuart 1955), so to address this issue a modified Mann–Kendall test technique has been developed that takes the lag-ith autocorrelation of the time series into account and has proved robust in practice (Hamed & Rao 1998; Zhang et al. 2012). Wang et al. (2014) successfully applied this modified technique to detect trends in hydrometeorological time series with abrupt changes. Here, we used the modified Mann–Kendall test technique to determine whether a statistically significant (α = 0.05) temporal (i.e. decreasing or increasing) trend was present in the precipitation and runoff data. The modified technique is briefly described below; a more detailed treatment can be found in Hamed & Rao (1998) and Wang et al. (2014).

For a given hydro meteorological time series \(\{Y_1, Y_2, \ldots Y_n\}\) with a sample size of \(n\), its trend can be detected using the following seven sequential steps:

1. Compute the Sen’s slope (Sen 1968), \(Q\), of the time series using Equations (1) and (2):

\[
Q = \begin{cases} 
\frac{T_m + 1}{2} & \text{if } m = \frac{n(n-1)}{2} \text{ is odd} \\
\frac{T_m + T_m + 1}{2} & \text{if } m = \frac{n(n-1)}{2} \text{ is even}
\end{cases}
\]
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3. Compute the lag-ith serial autocorrelation coefficients \( \rho(i) \) (Equation (3)) using these ranks (Sen 1968; Zetterqvist 1991) and ensure the coefficients are statistically significant at a significance level of \( \alpha = 0.05 \) based on \( t \)-test statistics (Equation (4)):

\[
\rho(i) = \frac{\sum_{k=1}^{n-i} (y_k - \bar{y})(y_{k+i} - \bar{y})}{\left[ \sum_{k=1}^{n-i} (y_k - \bar{y})^2 \right]^{0.5}}
\]  

\[
t_i = \frac{\rho(i)}{\sqrt{1 - \rho(i)^2}}
\]

where \( \bar{y} \) is the mean of ranks \( \{y_1, y_2, \ldots, y_n\} \); and \( i = 1, 2, \ldots, n - 5 \).

4. Compute the ratio of \( \frac{n}{n_S^*} \) and the variance \( \text{var}^*(S) \) as:

\[
\frac{n}{n_S^*} = 1 + \frac{2}{n(n-1)(n-2)}
\]

\[
\sum_{i=1}^{n-3} [(n-i)(n-i-1)(n-i-2) \cdot \rho_i(i)]
\]

\[
\text{var}^*(S) = \frac{n(n-1)(2n+5) - \sum_{p=1}^{n_p} [m_p(m_p-1)(2m_p+5)]}{18}
\]

where \( n_p \) is the number of distinct ties, and \( m_p \) is the number of tied data points in the \( p \)-th tie.

5. Compute the conventional Mann–Kendall statistics of \( S \) as (Mann 1945; Kendall 1970):

\[
S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \text{sign}(y_j - y_k)
\]

\[
\text{sign}(y_j - y_k) = \begin{cases} 
1 & \text{if } y_j > y_k \\
0 & \text{if } y_j = y_k \\
-1 & \text{if } y_j < y_k 
\end{cases}
\]

where \( k = 1, 2, \ldots, n-1; j = k + 1, k + 2, \ldots, n \).

6. Compute the modified Mann–Kendall test statistics of \( Z^* \) as (Hamed & Rao 1998):

\[
Z^* = \begin{cases} 
\frac{S - 1}{\sqrt{\text{var}^*(S)}} & \text{if } S > 0 \\
0 & \text{if } S = 0 \\
\frac{S + 1}{\sqrt{\text{var}^*(S)}} & \text{if } S < 0 
\end{cases}
\]

7. Judge the trend of the time series for precipitation: a positive \( Z^* \) indicates an increasing trend, whereas a negative \( Z^* \) indicates a decreasing trend. A \( Z^* \) of greater than the standard normal 95th percentile signifies a statistically significant trend at a significance level of \( \alpha = 0.05 \).

Dependence of runoff on factors related to climate and urbanization

Correlation coefficients were computed between runoff and each of the factors related to climate and urbanization to measure how much the factors influence runoff. A correlation coefficient of one indicates a perfect positive relationship (i.e. runoff increases with increase of the factor and vice versa), whereas a correlation coefficient of negative one indicates a perfectly negative relationship (i.e. runoff increases with decrease of the factor and vice versa). For correlation coefficients with an absolute value between zero and one, a larger value indicates a stronger relationship and a zero correlation coefficient means there is no relationship. The correlation coefficient between any two variables \( \hat{e}_x \) and \( y_a \) of interest can be
computed as:

\[ r_k(z, y) = \frac{\sum_{x=1}^{n-k} (z_x - \bar{z})(y_{x+k} - \bar{y})}{\left( \sum_{x=1}^{n} (z_x - \bar{z})^2 \right)^{1/2} \left( \sum_{x=1}^{n} (y_x - \bar{y})^2 \right)^{1/2}} \]  \hspace{1cm} (10)

where \( z \) and \( y \) are the vectors of \( z_x \) and \( y_x \) with \( n \) elements; \( r_k(z, y) \) is the correlation coefficient; and \( k \) is the index number of the elements.

A relationship can be judged statistically significant at a given confidence level if \( |r_k(x, y)| \) is greater than Fisher’s smallest correlation coefficient \( (|r_{0k}|_{\text{min}}) \) for a confidence level of \( p = 1 - \alpha \) (Ding & Deng 1988). If \( |r_k(x, y)| < |r_{0k}|_{\text{min}} \), \( z \) and \( y \) are judged to be independent; and if \( |r_k(x, y)| \geq |r_{0k}|_{\text{min}} \), \( z \) and \( y \) are judged to be correlated with each other, with a larger value of \( |r_k(x, y)| \) indicating a stronger correlation.

\[ |r_{0k}|_{\text{min}} \] can be computed as:

\[ |r_{0k}|_{\text{min}} = \frac{t_p}{\sqrt{t_p^2 + n - 2}} \]  \hspace{1cm} (11)

where \( t_p \) is the critical value of the student-t distribution that gives a cumulative probability of \( p \).

**Synthesis of runoff-influencing factors**

In order to further understand how various factors of climate and urbanization interact to influence runoff, those factors with a higher dependence (i.e. a greater correlation coefficient) were synthesized using principal component analysis (PCA), an eigenvector-based multivariate analysis method that converts a high-dimensional into a lower-dimensional data space and can be used to reveal the internal data structure. PCA uses an orthogonal transformation algorithm to convert correlated variables into a set of linearly uncorrelated new variables (i.e. principal components). The number of PCs is less than or equal to the total number of original variables. This transformation is defined such that the first PC has the largest possible variance, and each succeeding component in descending order has the highest variance possible under the constraint that it is orthogonal to the preceding components. All PCs are guaranteed to be independent if the original variables are jointly normally distributed. For this study, we used the data processing system (DPS) software package developed by Tang & Zhang (2003).

**RESULTS**

**Temporal variations in the precipitation and runoff**

At an annual scale, although the precipitation fluctuated from year to year with an insignificant decreasing trend (\( p\)-value = 0.685), the runoff exhibited an obvious decreasing trend (\( p\)-value = 0.001) (Figure 2 and Table 2). The
study year with the most precipitation did not have the greatest runoff, but the year with the least precipitation did have the smallest runoff. The maximum precipitation of 494 mm occurred in 2012, but the maximum runoff of 26 mm was actually recorded in 1998. In contrast, the minimum precipitation of 167 mm in 2011 generated the minimum runoff of 0.1 mm in the same year. However, regardless of any fluctuations in the precipitation, the runoff tended to monotonically decrease with year, with a steeper declining trend before 2005 than after. The precipitation-runoff relationship prior to 2005 was obviously different from the trend before 2005 than after. The annual average runoff was 3.3 mm, with a maximum of 138 mm in 2003 and a minimum of 21 mm in 2000, while the annual average runoff was 2.5 mm, with a maximum of 12.2 mm in 1997 and a minimum of 0.1 mm in 2011. Again, the dry-seasonal maximum precipitation and maximum runoff did not occur in the same year (Figure 2). The dry-season precipitation also fluctuated from year to year, with no clear decreasing trend (p-value = 0.444), whereas the runoff exhibited a very significant decreasing trend (p-value = 0.000). In contrast with the wet season data, the dry season runoff exhibited a consistent declining trend across the entire analysis period (1997–2012), with no inflection point. For both the wet and dry seasons, the annual average runoff from 1997 to 2005 was over 80% greater than that from 2006 to 2012 (Table 3). This is comparable with that measured at the annual scale (83.2%).

At a monthly scale, as expected, the three winter months (December–February) had a zero runoff, while the wettest month of July had the highest precipitation (84 mm) and runoff (2.1 mm) (Figure 4). The peak runoff in March was due to melting snow, followed by low runoffs in April–June, probably due to the increased evapotranspiration resulting from warmer temperatures, windy and dry conditions, and growing vegetation. The relatively high levels of precipitation in August and September failed to generate proportional runoffs, possibly because of the high transpiration of maturing vegetation; the runoff in October and November, when vegetation normally wilts and/or becomes dormant, was proportional to the precipitation in those months.

Table 2 | Historical trends of runoff and precipitation in the study watershed revealed by the modified Mann–Kendall test

<table>
<thead>
<tr>
<th>Item</th>
<th>Time scale</th>
<th>Sen’s slope</th>
<th>S</th>
<th>Z*</th>
<th>Trend</th>
<th>p-value(^{ab})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Runoff</td>
<td>Annual</td>
<td>-0.601</td>
<td>-74</td>
<td>-3.287</td>
<td>Downward</td>
<td>0.001(^a)</td>
</tr>
<tr>
<td></td>
<td>Wet season</td>
<td>-0.232</td>
<td>-55</td>
<td>-2.431</td>
<td>Downward</td>
<td>0.015(^a)</td>
</tr>
<tr>
<td></td>
<td>Dry season</td>
<td>-0.306</td>
<td>-88</td>
<td>-3.917</td>
<td>Downward</td>
<td>0.000(^a)</td>
</tr>
<tr>
<td>Precipitation</td>
<td>Annual</td>
<td>-1.513</td>
<td>-10</td>
<td>-0.405</td>
<td>Downward</td>
<td>0.685</td>
</tr>
<tr>
<td></td>
<td>Wet season</td>
<td>-0.572</td>
<td>-2</td>
<td>-0.045</td>
<td>Downward</td>
<td>0.964</td>
</tr>
<tr>
<td></td>
<td>Dry season</td>
<td>-1.344</td>
<td>-18</td>
<td>-0.765</td>
<td>Downward</td>
<td>0.444</td>
</tr>
</tbody>
</table>

\(^{a}\) Sen’s slope: Equation (1); S: Equation (7); and Z*: Equation (9).

\(^{b}\): significant at a significance level of \(\alpha = 0.05\).
Regardless of the time scale, although the average precipitation readings from 2006 to 2012 were comparable with those from 1997 to 2005, the annual average monthly runoff amounts from 2006 to 2012 were consistently smaller than those from 1997 to 2005 (Figures 2 and 3(b)). This indicates that alteration of the watershed characteristics (i.e. urbanization) rather than climate change is more likely to be responsible for the reduced runoff since 2006, which

Figure 3 | Plots showing the (a) DMC and (b) scatter plot of the annual runoff and precipitation.

Table 3 | Comparison of the annual average runoffs in the study watershed for 1997–2005 and 2006–2012

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual</td>
<td>9.0</td>
<td>1.5</td>
<td>-83.2</td>
</tr>
<tr>
<td>Wet season</td>
<td>5.2</td>
<td>0.8</td>
<td>-84.9</td>
</tr>
<tr>
<td>Dry season</td>
<td>5.9</td>
<td>0.7</td>
<td>-80.9</td>
</tr>
</tbody>
</table>
can be further verified by looking at the runoff coefficient. The annual runoff coefficient tended to become smaller with time (Figure 5(a)) and its decreasing trend is significant ($p$-value = 0.000, Table 4). Although the runoff in the wet season was larger than in the dry season, the runoff coefficient for the wet season was smaller. As with the annual runoff coefficient, the runoff coefficients for both the wet and dry seasons tended to become smaller, with significant decreasing trends ($p$-value < 0.003) (Table 4). The annual average runoff coefficient for the wet season was 0.01, with a minimum of close to zero in 2010 and 2011 and a maximum of 0.06 in 1998, whereas the annual average runoff coefficient for the dry season was 0.04, with a maximum of 0.15 in 2000 and a minimum of 0.001 in 2012 (Figure 5(a)). Regardless of the time scale, the annual average runoff coefficient from 1997 to 2005 was over 70% smaller than that from 2006 to 2012 (Table 4). For any given month, the runoff coefficient before 2006 was consistently larger than that in later years (Figure 5(b)). The runoff coefficient in March (0.266) was largest because it was based on the ratio of the runoff generated by the melting of the snowpack that had accumulated over the three winter months to the precipitation in March alone. Thus, this largest runoff coefficient should not be interpreted to indicate that the conversion percentage of precipitation into runoff in March was actually the highest. Nevertheless, the runoff coefficient for a high precipitation month such as July was not necessarily greater than that for one with a low precipitation such as October (Figure 5(b) versus Figure 4), indicating that the study watershed likely has a relatively sophisticated precipitation-runoff relationship.

**Temporal variations in climate and urbanization**

A watershed’s runoff can be affected by climate, watershed characteristics such as land use, and human activity such as water consumption (Juckem et al. 2008; Tu 2009; Franczyk & Chang 2009; Qi et al. 2009; Hejazi & Markus 2009; Wang et al. 2013). For this study we analyzed six climate variables, namely precipitation, evaporation, relative humidity, sunshine duration, temperature, and wind speed. All the climate variables exhibited insignificant decreasing trends at a significance level of $\alpha = 0.05$ (Figure 6 and Table 6). For any given climate variable, its annual average from 1997 to 2005 was very close to that from 2006 to 2012, with a difference of less than 5% (Table 7).

Averaged across the 4 years from 1997 to 2011, the major land uses across the watershed were 80% fallow, 10% vegetation, and 10% urban and water. However, there was a rapid expansion of urbanized areas around 2005 at the expense of other types of land uses (Figure 7). From 1997 to 2011, the urbanized area increased from less than 1% to nearly 12% of the total watershed area (i.e. more than twelve-fold), while from 2005 to 2011, the urbanized area increased almost ten-fold (Table 8). In contrast, the water and fallow areas decreased substantially, with the water area
decreasing from 2.8% in 1997 to 0.5% in 2011 (i.e. more than five-fold) and the fallow area from 82.4 to 68.8%. The vegetation area increased slightly, by about 5%, which can be attributed to the policy of tree-planting and agricultural development since 2000.

The study watershed includes two major metropolitan areas, namely Dengsheng District and Ejin Horo Banner (Figure 1), so their GDP and population were selected as
the surrogates for the area’s socioeconomic development and urbanization levels. Here, GDP = PIP + SIP + TIP. In addition, CIP, which is included as a secondary industry product, determines the impervious areas and thus was used for the urbanization analysis. From 1997 to 2012, the GDP and its components, population and urbanized area, exhibited consistently increasing trends (Figure 8), which accelerated markedly after 2005. The increasing trend for the urbanized area was almost synchronized with those for SIP and TIP, indicating that for the study watershed, urbanization and socioeconomic development might be equivalent.

Except for population, the annual average for each of the socioeconomic indexes from 2006 to 2012 was more than...
twice that from 1997 to 2005 (Table 9). This coincided with a more than ten-fold increase in both TIP and CIP, indicating that the study watershed experienced rapid urbanization after 2005, although the increases in population (20%) and PIP (100%) were relatively smaller than for the other socioeconomic indexes.

**Relationship between runoff and urbanization**

At the 95% confidence level, runoff was found not to be significantly correlated with any of the climate factors ($|r_k| < |r_{k_{lim}}| = 0.495$), but it was judged to be significantly correlated with the socioeconomic variables (i.e. urbanization) ($|r_k| > |r_{k_{lim}}|$) (Table 10). Thus, the climate variables were dropped from the further analysis. Because the correlations tended to become better with natural log-transformed data, the relationship was established in terms of transformed runoff and socioeconomic variables.

The socioeconomic variables were found to be highly correlated (Table 11). The PCA analysis (Tables 12 and 13) showed that the first PC (Equation (12)) explained more than 99% of the variances presented in the data, and thus was used as the synthesized variable of the socioeconomic variables. The synthesized variable, FPC, was determined as:

$$FPC = 0.409 \cdot population + 0.409 \cdot GDP + 0.406 \cdot PIP + 0.407 \cdot SIP + 0.408 \cdot TIP + 0.409 \cdot CIP \tag{12}$$

Regardless of the time scale, the plots of natural log-transformed runoff versus FPC (Figure 8) show a strong functional relationship between runoff and FPC ($R^2=0.616$ at the annual scale, 0.439 for the wet season, and 0.924 for the dry season), indicating that for the study watershed, urbanization had a dramatically negative impact on runoff. The decreasing trend exhibited by the runoff data for the period from 2006 to 2012 was found to be much steeper than for 1997 to 2005, especially for the dry season runoff (Figure 8).

**DISCUSSION**

The runoff from the study watershed did not increase with increasing urbanized area, but instead decreased by about 80% when the urbanized area increased from 0.8 to 12% between 1997 and 2011. This disagrees with the findings of several previous studies (Choi & Deal 2008; Franczyk & Chang 2009; Du et al. 2012) but is consistent with others (Sun et al. 2007; Gao et al. 2011). Choi & Deal (2008) studied the impact of land use changes on the hydrology of the Kishwaukee River basin in the Midwest USA and found that changing land use resulted in a small change in total runoff. As a result of a very high population growth rate, the annual runoff was predicted to increase by only 1.7% by 2050. Franczyk & Chang (2009) predicted that an expansion of 8–15% of the urban land use throughout the Rock Creek basin in Oregon, also in the USA, would result in a 2.3–2.5% increase in annual runoff, while Du et al. (2012) predicted a mere 0.2% increase in annual runoff for an increase in the impervious area from 3 to 31% in the...
<table>
<thead>
<tr>
<th>Year</th>
<th>Urban</th>
<th>Water</th>
<th>Vegetation&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Fallow&lt;sup&gt;b&lt;/sup&gt;</th>
<th>1997</th>
<th>2000</th>
<th>2005</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>16.331</td>
<td>54.645</td>
<td>271.280</td>
<td>1,607.476</td>
<td>0.838</td>
<td>2.803</td>
<td>13.914</td>
<td>82.446</td>
</tr>
<tr>
<td></td>
<td>16.477</td>
<td>42.526</td>
<td>197.969</td>
<td>1,692.759</td>
<td>0.845</td>
<td>2.181</td>
<td>10.154</td>
<td>86.820</td>
</tr>
<tr>
<td></td>
<td>30.051</td>
<td>15.801</td>
<td>211.321</td>
<td>1,692.559</td>
<td>1.541</td>
<td>0.810</td>
<td>10.838</td>
<td>86.810</td>
</tr>
<tr>
<td></td>
<td>232.577</td>
<td>10.615</td>
<td>365.597</td>
<td>1,340.942</td>
<td>11.929</td>
<td>0.544</td>
<td>18.751</td>
<td>68.776</td>
</tr>
</tbody>
</table>

<sup>a</sup>Forest, grass, and crops.

<sup>b</sup>Sparse vegetation, bare land, and unused land.
Qinhuai River basin of China. However, other studies have reported that runoff tends to decrease as a result of human activity. Gao et al. (2014) found that the cumulative streamflow was reduced by 17.8% between 1957 and 2008 due to human activity in the middle reaches of the Yellow River in China, and Sun et al. (2007) also reported a decreasing trend in runoff resulting from human activity between 1961 and 2005 in the Upper Chao River watershed of China.

For the Wulanmulun River watershed, the fluctuations in the climate variables did not exhibit any significant trends (Figure 6 and Table 6), whereas the urbanized area and other socioeconomic indexes consistently showed increasing trends (Figure 8 and Table 9). Thus, it appears likely that urbanization, rather than climate, is the major cause of the decrease in runoff observed (Figure 9 and Table 10). One explanation is that although the increased activity. Gao et al. (2011) found that the cumulative streamflow was reduced by 17.8% between 1957 and 2008 due to human activity in the middle reaches of the Yellow River in China, and Sun et al. (2007) also reported a decreasing trend in runoff resulting from human activity between 1961 and 2005 in the Upper Chao River watershed of China.

For the Wulanmulun River watershed, the fluctuations in the climate variables did not exhibit any significant trends (Figure 6 and Table 6), whereas the urbanized area and other socioeconomic indexes consistently showed increasing trends (Figure 8 and Table 9). Thus, it appears likely that urbanization, rather than climate, is the major cause of the decrease in runoff observed (Figure 9 and Table 10). One explanation is that although the increased

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Population (10^4)</td>
<td>35</td>
<td>41</td>
<td>+20</td>
</tr>
<tr>
<td>GDP (10^8 ¥)</td>
<td>93</td>
<td>902</td>
<td>+868</td>
</tr>
<tr>
<td>PIP (10^8 ¥)</td>
<td>3.5</td>
<td>7.2</td>
<td>+102</td>
</tr>
<tr>
<td>SIP (10^8 ¥)</td>
<td>49.9</td>
<td>438</td>
<td>+778</td>
</tr>
<tr>
<td>TIP (10^8 ¥)</td>
<td>39.8</td>
<td>458</td>
<td>+1,052</td>
</tr>
<tr>
<td>CIP (10^8 ¥)</td>
<td>18.3</td>
<td>204</td>
<td>+1,011</td>
</tr>
</tbody>
</table>

*PIP: primary industry products; SIP: secondary industry products; TIP: tertiary industry products; and CIP: construction industry products.

Figure 8 | Temporal variations of: (a) GDP and population; and (b) industry-specified products and urbanized area.

Table 9 | Comparison of urbanization parameters for 1997–2005 and 2006–2012

Figure 9 | Temporal variations of runoff in a rapidly urbanizing semi-arid Chinese watershed.

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impervious area resulting from urbanization would tend to make the peak discharge higher, this runoff was being intercepted and collected by various drainage facilities and used for environment greening and industrial development in this semi-arid region of China, leaving less runoff to flow into the Wulanmulun River. Another explanation is that because of the increase in vegetated areas (Table 8) due to increased cultivation and environment greening, more runoff was retained and transpired by vegetation. Alternatively, the groundwater level may have receded because a large amount of groundwater was pumped out to meet the water demands of the urban development, increasing the soil infiltration capability and thus causing the runoff to decrease. Finally, the runoff may simply have been consumed by people and/or manufacturers. The data clearly show, however, that the rapid urbanization from 2006 to 2012 negatively affected the runoff in this watershed, as indicated by the obvious inflection point in the DMC (Figure 3(a)) around 2005, signaling that the mean annual runoff from 1997 to 2005 was much larger than that from 2006 to 2012 (Table 3).

For any given time scale, the maximum precipitation and the maximum runoff did not occur in the same year, which seems to violate the general principles of hydrology.

**Table 10 | Correlation coefficients between runoff and climate as well as socioeconomic variables**

<table>
<thead>
<tr>
<th>Type</th>
<th>Variable</th>
<th>Annual runoff</th>
<th>Wet season runoff</th>
<th>Dry season runoff</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Obs.</td>
<td>LogT</td>
<td>Obs.</td>
</tr>
<tr>
<td>Climate</td>
<td>Sunshine duration</td>
<td>0.056</td>
<td>0.189</td>
<td>-0.115</td>
</tr>
<tr>
<td></td>
<td>Relative humidity</td>
<td>0.474</td>
<td>0.483</td>
<td>0.610*</td>
</tr>
<tr>
<td></td>
<td>Temperature</td>
<td>0.322</td>
<td>0.200</td>
<td>0.287</td>
</tr>
<tr>
<td></td>
<td>Wind speed</td>
<td>0.128</td>
<td>0.206</td>
<td>0.085</td>
</tr>
<tr>
<td></td>
<td>Evaporation</td>
<td>-0.005</td>
<td>-0.081</td>
<td>-0.171</td>
</tr>
<tr>
<td></td>
<td>Precipitation</td>
<td>0.314</td>
<td>0.251</td>
<td>0.494</td>
</tr>
<tr>
<td>Socio-economic</td>
<td>Population</td>
<td>-0.687*</td>
<td>-0.782*</td>
<td>-0.520*</td>
</tr>
<tr>
<td></td>
<td>GDP</td>
<td>-0.503*</td>
<td>-0.775*</td>
<td>-0.366</td>
</tr>
<tr>
<td></td>
<td>PIP</td>
<td>-0.640*</td>
<td>-0.734*</td>
<td>-0.474</td>
</tr>
<tr>
<td></td>
<td>SIP</td>
<td>-0.492</td>
<td>-0.790*</td>
<td>-0.352</td>
</tr>
<tr>
<td></td>
<td>TIP</td>
<td>-0.512*</td>
<td>-0.753*</td>
<td>-0.378</td>
</tr>
<tr>
<td></td>
<td>CIP</td>
<td>-0.482</td>
<td>-0.781*</td>
<td>-0.347</td>
</tr>
</tbody>
</table>

Obs.: calculated using observed data; LogT: calculated using natural log-transformed data; PIP: primary industry products; SIP: secondary industry products; TIP: tertiary industry products; and CIP: construction industry products.

*: significant correlation at 95% confidence level.

**Table 11 | Statistics and correlation coefficients for the socioeconomic variables**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Average</th>
<th>Standard deviation</th>
<th>Population</th>
<th>GDP</th>
<th>PIP</th>
<th>SIP</th>
<th>TIP</th>
<th>CIP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population</td>
<td>3.618</td>
<td>0.108</td>
<td>1.000</td>
<td>0.994</td>
<td>0.990</td>
<td>0.990</td>
<td>0.990</td>
<td>0.997</td>
</tr>
<tr>
<td>GDP</td>
<td>5.356</td>
<td>1.358</td>
<td>0.994</td>
<td>1.000</td>
<td>0.984</td>
<td>0.996</td>
<td>0.996</td>
<td>0.997</td>
</tr>
<tr>
<td>PIP</td>
<td>1.542</td>
<td>0.458</td>
<td>0.990</td>
<td>0.984</td>
<td>1.000</td>
<td>0.975</td>
<td>0.984</td>
<td>0.988</td>
</tr>
<tr>
<td>SIP</td>
<td>4.712</td>
<td>1.263</td>
<td>0.990</td>
<td>0.996</td>
<td>0.975</td>
<td>1.000</td>
<td>0.984</td>
<td>0.992</td>
</tr>
<tr>
<td>TIP</td>
<td>4.508</td>
<td>1.551</td>
<td>0.990</td>
<td>0.996</td>
<td>0.984</td>
<td>0.984</td>
<td>1.000</td>
<td>0.993</td>
</tr>
<tr>
<td>CIP</td>
<td>3.738</td>
<td>1.491</td>
<td>0.997</td>
<td>0.997</td>
<td>0.988</td>
<td>0.992</td>
<td>0.993</td>
<td>1.000</td>
</tr>
</tbody>
</table>

PIP: primary industry products; SIP: secondary industry products; TIP: tertiary industry products; and CIP: construction industry products.
One possible reason is that the maximum precipitation might be due to highly localized heavy storms in areas near the rain gauges that did not actually generate large amounts of runoff at the outlet of the study watershed. Another possible explanation is that the transpiration demand tends to exponentially increase with precipitation because of the better growth of vegetation (Jiang et al. 1999; Wang et al. 2013). As a result, the soil moisture may be reduced to a level at which soil storage became phenomenal. Once the total increased transpiration demand and soil storage exceeded the increase in precipitation, which could be the case for a year with very high precipitation, the increased precipitation would be associated with a decreased runoff (Figure 3(a)).

The runoff coefficient in the wet season was found to be smaller than that in the dry season (Figure 5(a)). This is consistent with the findings reported by Muleta (2012), but seems contrary to both common sense and the findings of Tang et al. (2007) and van Werkhoven et al. (2008). Once again, if the wet season experienced heavy storms in the areas near the rain gauges, this would not generate large amounts of runoff at the outlet of the study watershed. It is possible that the precipitation in the dry season might be more uniformly distributed across the watershed, and thus more accurately represented by the observations at the rain gauges. Another possibility is that the precipitation in the wet season, which is also the growing season, tends to be intercepted, infiltrated, and transpired by vegetation, leading to a lower conversion percentage of precipitation to runoff. The infiltration in the wet season might partially be converted to runoff in the succeeding dry season, making the observed runoff in the dry season larger than the runoff that was generated by the precipitation that actually occurred in the dry season. The third possible explanation is that the rapid urbanization from 2006 to 2012 profoundly altered the natural runoff-generation mechanism and thus negatively affected the runoff. The increased number of water storage facilities (e.g. ponds) and diversions might also change the runoff distribution across the different seasons, making the observed runoff in a season a poor match for the observed precipitation in the same season. For example, the runoff generated in a wet season could

Table 12 | Normalized eigenvectors of the PCs

<table>
<thead>
<tr>
<th>Variable</th>
<th>PC1</th>
<th>PC2</th>
<th>PC3</th>
<th>PC4</th>
<th>PC5</th>
<th>PC6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population</td>
<td>0.409</td>
<td>0.090</td>
<td>0.275</td>
<td>-0.683</td>
<td>0.530</td>
<td>-0.043</td>
</tr>
<tr>
<td>GDP</td>
<td>0.409</td>
<td>-0.269</td>
<td>-0.203</td>
<td>0.213</td>
<td>0.044</td>
<td>-0.819</td>
</tr>
<tr>
<td>PIP</td>
<td>0.406</td>
<td>0.771</td>
<td>0.244</td>
<td>0.426</td>
<td>-0.022</td>
<td>-0.001</td>
</tr>
<tr>
<td>SID</td>
<td>0.407</td>
<td>-0.568</td>
<td>0.423</td>
<td>0.403</td>
<td>0.113</td>
<td>0.396</td>
</tr>
<tr>
<td>TID</td>
<td>0.408</td>
<td>0.029</td>
<td>-0.800</td>
<td>0.024</td>
<td>0.160</td>
<td>0.407</td>
</tr>
<tr>
<td>CID</td>
<td>0.409</td>
<td>-0.050</td>
<td>0.063</td>
<td>-0.379</td>
<td>-0.823</td>
<td>0.062</td>
</tr>
</tbody>
</table>

*PIP: primary industry products; SIP: secondary industry products; TIP: tertiary industry products; and CIP: construction industry products.

Table 13 | Parameters of the PC analysis

<table>
<thead>
<tr>
<th>Component</th>
<th>Eigenvalues</th>
<th>Percent (%)</th>
<th>Cumulative percent (%)</th>
<th>Chi-square ($\chi^2$)</th>
<th>Degree freedom (df)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC1</td>
<td>5.950</td>
<td>99.2</td>
<td>99.2</td>
<td>340.4</td>
<td>20</td>
<td>0.000</td>
</tr>
<tr>
<td>PC2</td>
<td>0.027</td>
<td>0.5</td>
<td>99.7</td>
<td>81.6</td>
<td>14</td>
<td>0.000</td>
</tr>
<tr>
<td>PC3</td>
<td>0.014</td>
<td>0.2</td>
<td>99.9</td>
<td>66.3</td>
<td>9</td>
<td>0.000</td>
</tr>
<tr>
<td>PC4</td>
<td>0.006</td>
<td>0.1</td>
<td>100.0</td>
<td>53.0</td>
<td>5</td>
<td>0.000</td>
</tr>
<tr>
<td>PC5</td>
<td>0.003</td>
<td>0.0</td>
<td>100.0</td>
<td>43.6</td>
<td>2</td>
<td>0.000</td>
</tr>
<tr>
<td>PC6</td>
<td>0.000</td>
<td>0.0</td>
<td>100.0</td>
<td>0.0</td>
<td>0</td>
<td>1.000</td>
</tr>
</tbody>
</table>
be temporally stored in a pond and then released in the succeeding dry season for irrigation.

**CONCLUSIONS**

This study examined temporal trends in the runoff and the possible influence of urbanization in the rapidly-developing Wulanmulun River watershed of China for the years 1997 to 2012. The examination was conducted at annual, seasonal, and monthly time scales using a data-driven approach consisting of data exploratory analysis, the modified Mann–Kendall method, and PCA. Time series data for land use, hydrometeorology, and socioeconomics were also utilized. The results revealed that the runoff from the study watershed exhibited a strong decreasing trend regardless of the time scale. The average runoff from 1997 to 2005 was much larger than that from 2006 to 2012 because of the rapid
urbanization the region has experienced since 2006. This rapid urbanization has greatly altered the natural runoff-generation mechanism and runoff distribution across the year. For the study watershed, the important runoff-influencing, urbanization-related variables were found to be population and GDP and its components, namely primary industry products, secondary industry products, and tertiary industry products. Further, the fluctuations in the climate variables (e.g. precipitation) from year to year did not have a major impact on the decreasing trend in the study watershed's runoff. The results can be directly used by policy makers and planners/managers to develop practical measures to minimize the impacts of urbanization on water resources in the Wulanmulun River watershed. Moreover, this study demonstrates how to separate the effect of urbanization from that of climate change on runoff in a long term run, which is a great contribution to the sustainable development of metropolitan centers.

Acknowledgements

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References


Ding, J. & Deng, Y. R. 1998 Stochastic Hydrology. Chengdu University of Science and Technology Press, Chengdu, China.


Im, S. J., Kim, H., Kim, C. & Jang, C. 2009 Assessing the impacts of land use changes on watershed hydrology using MIKE SHE. Environ. Geol. 57, 231–239.


Tu, J. 2009 Combined impact of climate and land use changes on streamflow and water quality in eastern Massachusetts, USA. J. Hydrol. 379, 268–283.


White, M. D. & Greer, K. A. 2006 The effects of watershed urbanization on the stream hydrology and riparian vegetation of Los Peñasquitos Creek, California. Landscape Urban Plan. 74, 125–138.
Xu, J. X. 2005 Sediment flux to the sea as influenced by changing human activities and precipitation: example of the Yellow River, China. Environ. Manag. 31 (3), 328–341.


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