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Geostatistical analysis of observed streamflow and its response to precipitation and temperature changes in the Yellow River

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Abstract The Yellow River's long-term hydrological regime and its responses to precipitation and temperature changes were investigated by producing a streamflow, precipitation and temperature relationship based on the observed data using ArcGIS geostatistical analysis. The results indicated that the runoff was sensitive to both precipitation and temperature and their relationship was nonlinear. This means that the water problem of the Yellow River is likely to be more critical in future scenarios involving global warming. The precipitation elasticity of the runoff was also calculated and discussed.

Key words ArcGIS geostatistical analysis; climatic change; water resources; Yellow River

INTRODUCTION

The Yellow River, the sixth longest river in the world and second longest river in China, has long been regarded as the "Cradle of Ancient Chinese Civilization" or as the "Mother River of China", because human inhabitants have existed in this region since prehistoric times (Wang *et al*., 2000). However, it has critical water resource problems because of extensive use of its limited water resources. The flow dry-up phenomenon, i.e. zero-flow in sections of the river channel, has occurred more and more often during the last 30 years and appears earlier and is more prolonged and extended. Recently, during the drought year of 1997, the river dry-up period lasted 227 days at the Li-Jin station, and for 330 days no water was discharged to the sea.

The water crisis of the Yellow River has raised some critical questions: Were human activities the only cause of the water shortage? Has the climate changed during the last several decades in the basin? and Does the water shortage have anything to do with climate warming? Answers to these questions are very important for decision making to ensure sustainable water resource utilization. Our previous study (Fu *et al*., 2004) showed that: (a) runoff has decreased in the last 4–5 decades, even allowing for the water taken for human uses; (b) the precipitation trend was not significant; and (c) the Yellow River watershed has become increasingly warmer over the last 4–5 decades with minimum temperature trends more significant than those of mean and maximum temperatures. That research though brought forth a new question: Is the decrease of runoff related to the climatic trend and, if so, how close are they? The primary objective of this research, then, was to study the relationships between the streamflow, precipitation and temperature, and the observed data with an aim towards revealing the relationship between climate parameters and runoff and the potential impacts of climatic change on the regional hydrological regime.

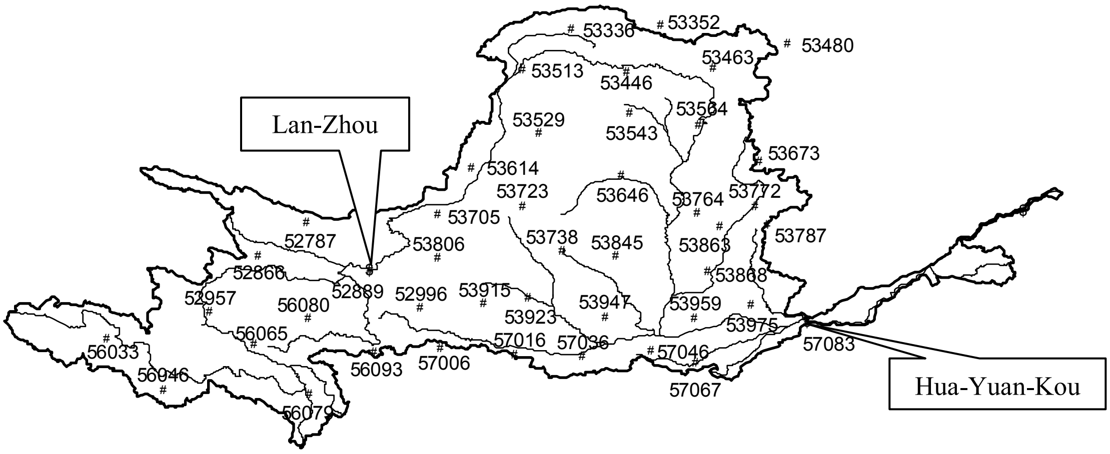

Fig. 1 Meteorological and hydrological stations used in this study.

DATA SETS

Climatic data

Forty-four standard meteorological stations (Fig. 1), storing the monthly precipitation and monthly means of daily mean temperature, were used for the study. These stations were among the 160 first-class meteorological stations in China with high-quality data. The 1957–1997 data were used to ensure that each year had at least 41 stations. These stations were maintained according to standard methods with the data released by the National Meteorological Administration of China.

Streamflow station

Two major hydrological gauges on the main streams of the Yellow River, Lan-Zhou and Hua-Yuan-Kou stations (Fig. 1) were used to evaluate the streamflow response to precipitation and temperature changes.

The Hua-Yuan-Kou station, with a catchment area of 730 036 km^2, was one key station on the main reach and is located where the middle reach and lower reach are divided. The runoff at this point usually reaches its maximum value because there is limited water flowing into the river channel downstream from this point as the riverbed is higher than the land outside the banks. The hydrological regime at this station represents an overview of the hydrological regime of the entire river basin.

The watershed above the Lan-Zhou station, with an area of 222 551 km^2 (about 29.3% of the total basin area), is the main source of runoff to the Yellow River and produces about 55.6% of the total annual average runoff. In addition this station is also a key station for the study in that the water drawn from the river is very limited in this region.

Natural flow data

Considering the influences of human activities such as water withdrawal from the river channel for irrigation, industry, and domestic use, and the role of dams to control the streamflow, the "real" or so-called "natural runoff" amount should be different from that observed at the hydrological gauges. The concept of natural runoff generally refers to the runoff produced under meteorological and physical geographical conditions, such as hydrological, geomorphic, geological, vegetation, soil and agricultural. The formula for estimating natural runoff is not complicated, but it requires detailed information, some of which is extremely difficult to collect. The difference between observed runoff and natural runoff generally results from three factors: (a) the amount of water directly abstracted from the river channel for irrigation, industry and domestic usage, and the amount returning to the downstream river channel after usage; (b) the amount of water controlled by dams, including extra water losses through evaporation, seepage, etc. due to dams; and (c) the amount of water transported into and out of the watershed. The Yellow River Commission has conducted a great deal of complex work to collect data and build the natural runoff series. Although some hydrologists question the accuracy of this natural runoff series, the results of natural runoff are widely used instead of observed runoff in water resource management and planning and hydrological engineering projects.

HYDROCLIMATIC REGIME OF THE YELLOW RIVER BASIN

Long-term water balance

The average annual precipitation for 1957–1997 was 455.8 mm for the entire Yellow River basin based on our 44 stations. The average annual streamflow at Hua-Yuan-Kou station is 57.47 billion m^3, or 78.7 mm of runoff depth. The runoff coefficient is only 0.173. The rest of the runoff, or about 82.7% of the regional precipitation, is consumed by evapotranspiration.

Year-to-year variation

The annual variations between precipitation and runoff have themselves varied significantly for the Yellow River basin. The annual precipitation maximum value was 1.92 times that of the minimum value and the annual runoff maximum value was 2.86 times that of the lowest flow year during the 41-year period of 1957–1997 (Table 1). The precipitation and temperature data were the spatial average values for 44 stations with each individual station having much larger variations than this cumulative average. The runoff data were from Hua-Yuan-Kou station.

Table 1 Mean, standard deviation and extreme values of precipitation, runoff, and temperature for the Yellow River basin (1957–1997).

	Mean	Standard deviation	Minimum		Maximum	
			Value	%	Value	%
Precipitation (mm)	455.8	67.8	333.4	73.2	640.7	140.6
Runoff (10^9 m^3)	57.5	13.44	34.6	60.2	98.9	172.1
Temperature (°C)	7.233	0.392	6.345		8.086	

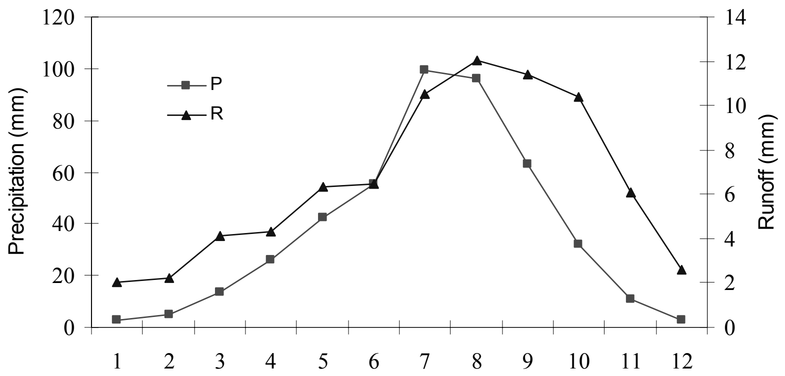

Fig. 2 Monthly precipitation and runoff for the Yellow River basin.

Seasonal/monthly variation

Both precipitation and runoff have obvious seasonal/monthly variations (Fig. 2). They have almost the same seasonal pattern, except that the runoff had a time lag and its peak time lasted longer. The temperature has the same pattern as runoff, with July as the hottest month, followed closely by August and June.

Spatial pattern

Although the annual precipitation is 400–600 mm in most regions of the Yellow River basin, it varies spatially with a decreasing trend as one moves from the southeast to the northwest. The region with the highest precipitation was the north slopes of the Qinling Mountains with an annual average precipitation of about 800–900 mm. The driest area within the watershed was Hangjinhouqi of Inner Mongolia with less than 150 mm annual precipitation.

The distribution of the natural runoff of the Yellow River was also uneven in space due to precipitation. The two sub-watersheds above Lan-Zhou and between San-Men-Xia and Hua-Yuan-Kou are major sources of runoff, while the 163 000 km^2 sub-watershed between Lan-Zhou and He-Kou was a major area of runoff loss amounting to about one billion cubic metres.

STREAMFLOW RESPONSE TO PRECIPITATION AND TEMPERATURE

For each year, the annual departures for runoff, precipitation and temperature were calculated and plotted in a precipitation–temperature plane based on the methodology of Risbey & Entekhabi (1996). Each point in the plane represents one year of observed data in this figure. The contour of streamflow percentage change was then produced by Ordinary Kriging interpolation within ArcGIS 8.0 geostatistical analysis.

The result (Fig. 3) indicated that the runoff was sensitive not only to precipitation, but also to temperature. For example, a 30% precipitation increase resulted in a 45% increase of runoff if the temperature was normal, but only a 20% increase in runoff if the temperature was 0.8°C higher than the normal year. A 20% precipitation decrease

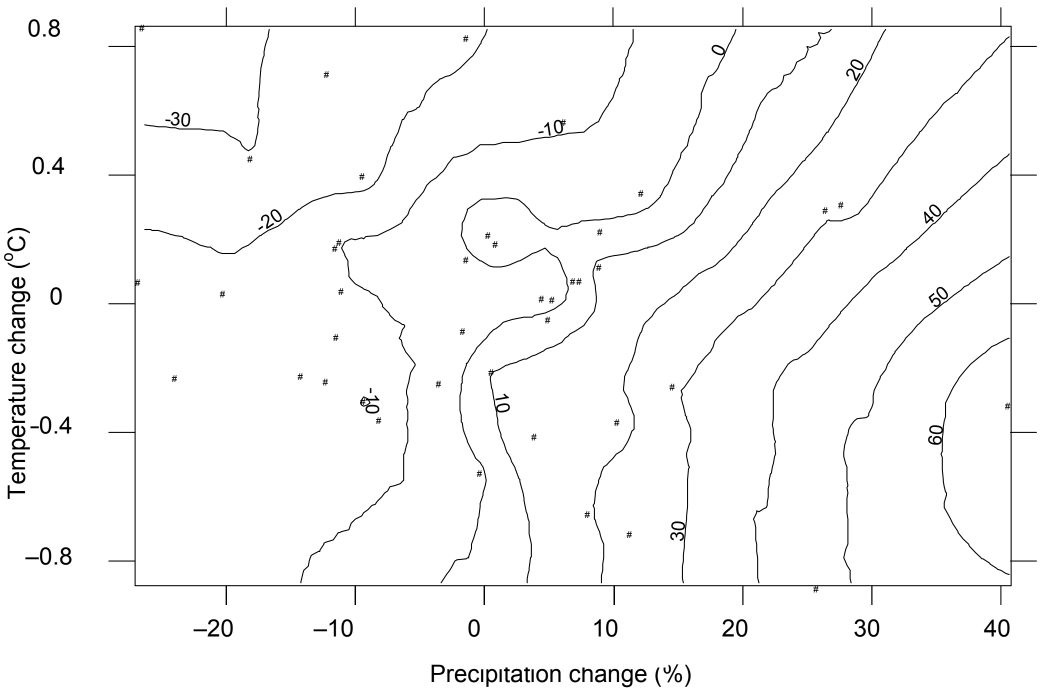

Fig. 3 Contour plot of percentage runoff change as a function of percentage precipitation change and temperature departure for the Yellow River basin.

would result in a 15% decrease of runoff if the temperature was normal and more than a 30% decrease in runoff if the temperature was 0.8°C higher than the normal year.

The regression analyses verified this conclusion. The R^2 was 0.6489 for the simple precipitation–runoff regression, while R^2 improved to 0.7298 when runoff, precipitation and temperature were included in the regression.

It is of no doubt that human activities are the number one factor leading to the water resources crisis (runoff decrease) in the Yellow River basin during the last 4–5 decades. However, this result has indicated that climatic change was also a major factor contributing to the runoff decrease because of evaporation increase associated with temperature increases.

This precipitation–runoff–temperature relationship based on data observed for the last 40 years was also consistent with the results of hydrological models estimating the effects of climate change. For example, Nijssen *et al.* (2001) used the variable macro-scale infiltration capacity hydrological model to assess the hydrological sensitivity of nine large-continent river basins to climate change, and predicted that the annual streamflow in the Yellow River basin would be reduced for all climate models, including those predicting an increase in annual precipitation. The data from this research corroborated their finding, showing that if the temperature were to increase by 0.8°C alongside a 10% increase of precipitation, then the runoff would decrease by more than 10%.

This result means the water issue in the Yellow River basin is likely to be more critical in future scenarios of global warming. The IPCC in its Third Assessment Report (Houghton *et al.*, 2001) states that "the globally averaged surface temperature is projected to increase by 1.4 to 5.8°C over the period 1990 to 2100" and "based on recent global model simulations, it is likely that nearly all land areas will warm more rapidly than the global average, particularly, those at northern high latitudes in the cold season. Most notable of these is the warming in the northern region of North America, and northern and central Asia, which exceeds global mean warming in each model by more than 40%." This will have serious consequences for urban water supply, agricultural production, industry development, and ecological systems in general.

NONLINEAR STREAMFLOW RESPONSE

A curious feature of Fig. 3 is that the response of streamflow to precipitation and temperature is nonlinear. This is to say that for a given precipitation and temperature increases/decrease, the percentage changes in streamflow larger than the percentage increase in precipitation and temperature magnitude. The differences between runoff percentage change and precipitation percentage change varied with precipitation and temperature. The larger the precipitation and temperature change, the greater the nonlinear response of runoff.

If we change the contour in Fig. 3 to the difference between runoff percentage change and precipitation percentage change, we obtain what is represented in Fig. 4, which clearly shows the nonlinear responses. Temperature also showed a very strong nonlinear signal with the difference between precipitation percentage change and run-off percentage change, especially for the scenario of precipitation increase.

Figure 5 shows the differences between runoff percentage change and precipitation percentage change as a function of precipitation percentage changes. The larger the

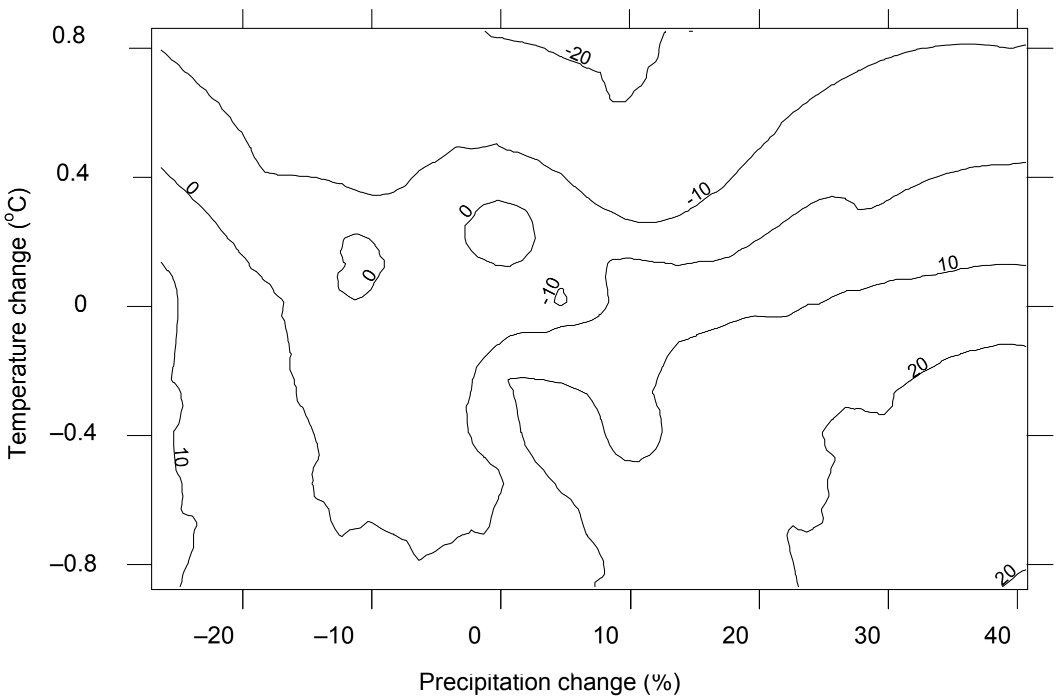

Fig. 4 Contour plot of the difference between percentage runoff change and percentage precipitation as a function of percentage precipitation change and temperature departure for the Yellow River basin.

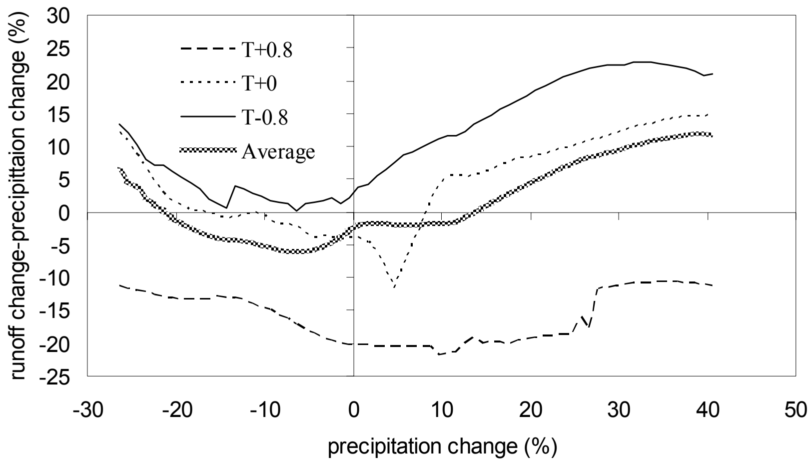

Fig. 5 Runoff change minus precipitation change as a function of precipitation change for the Yellow River basin at different temperature scenarios.

precipitation change, the higher the differences were. The temperature was really critical in this figure showing that the magnitude of the differences between runoff percentage change and precipitation percentage change was highly related to the temperature. The runoff response was always larger than the precipitation percentage change for the scenarios of temperature decrease and/or stability, and the runoff response was always less than precipitation percentage change for the temperature increase scenario. The later case resulted in evaporation increase and runoff decrease.

PRECIPITATION ELASTICITY OF RUNOFF

The precipitation elasticity of streamflow, developed by Sankarasubramanian & Vogel (2003) to quantify the sensitivity of streamflow to changes in precipitation, was used to estimate the precipitation elasticity of streamflow. The result indicated that it was 1.7 for the Yellow River, which means that a 1% change in precipitation will result in a 1.7% change in runoff. This value is in the range found for USA watersheds, by Sankarasubramanian & Vogel (2003), to be 1.0–2.5 for 1337 studied watersheds. However, our result indicated that this robust index was not fixed for a watershed and it varies with precipitation as well as temperature. A single elasticity cannot reflect the complicated responsive processes.

CONCLUSIONS

- The long-term water balance analyses indicate that the runoff coefficient was only 0.173 for the Yellow River, which indicates that the prominent characteristic of the water resources of the Yellow River is "short of water".
- The hydrological and climatic parameters are highly uneven in both time and spatial scales.
- Forty-one years of observed data were used to build the precipitation–runoff–

temperature relationship and the results indicated that runoff is sensitive to both precipitation and temperature.

- Besides human activities, climatic change was also a major factor contributing to the runoff decrease for the Yellow River basin.
- The runoff response exhibited substantial nonlinearity.
- ArcGIS geostatistical analysis is a useful tool to study impacts of climatic changes on regional hydrological regimes based on observed data.
- The precipitation elasticity of runoff was 1.7 for the Yellow River. However, our result indicated this value was not fixed and it varied with precipitation and temperature.

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