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El Niño-Southern Oscillation and water resources in Headwaters Region of the Yellow River: links and potential for forecasting

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Abstract

Many studies have examined that El Niño-Southern Oscillation (ENSO) could result in the variation of rainfall and runoff of different rivers across the world. In this paper, we will look specifically at the Headwaters Region of the Yellow River (HRYR) to explore the rainfall-ENSO and runoff-ENSO relationships and discuss the potential for water resources forecasting using these relationships. Cross-correlation analyses were performed to determine the significant correlation between rainfall, runoff and ENSO indicators (e.g. SOI, Niño 1.2, Niño 3, Niño 4, and Niño 3.4) and the lag period for each relationship. Main result include: (1) there are significant correlation at 95% confidence level during three periods, i.e. January and March, from September to November; (2) there were significant correlations between monthly streamflow and monthly ENSO indictors during three periods, i.e. JFM, June, and OND, with lag periods between one and twelve months. As ENSO events can be accurately predicted one to two years in advances using physical model of coupled ocean-atmosphere system, the lead time for forecasting runoff using ENSO indicator in the HRYR can be extent to one to thirty-six months. Therefore, ENSO may have potential as a powerful forecast tool for water resource in headwater regions of Yellow River.

1 Introduction

The El Niño-Southern Oscillation (ENSO) phenomenon is a natural part of the global climate system and results from the interactions between ocean and atmosphere that occur chiefly across its core region in the tropical-subtropical Pacific to Indian Ocean basins (Webster et al., 1998; Allan, 2000). Many studies have revealed that the occurrence of ENSO could result in the variability of climate (i.e., wind, temperature, and precipitation) throughout the tropics and in broad swaths of the extratropics simultaneously or with a lag of several months (Hamlet and Lettenmaier, 1999; Barton and Ramírez, 2004).The physical dynamics of ENSO are now reasonably well understood

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and the activity of ENSO can be predicted one to two years in advance using several coupled ocean/atmosphere models (Ropelewski, 1992; Piechota et al., 1997; Hamlet and Lettenmaier, 1999; Allan, 2000; Whitaker et al., 2001; Gutiérrez and Dracup, 2001). The lagged response of climate variability to ENSO and the predictability of ENSO make ENSO indicators have been a valuable predictor of regional climate with longer lead-time.

There have been numerous studies examining the relationship between ENSO and rainfall (Ropelewski and Halpert, 1986, 1987; Chiew et al., 1998; Chandimala and Zubair, 2007). These studies informed that rainfall variability could be significantly correlated with ENSO activity across different spatio-temporal scale. Therefore, streamflow, which is comprehensive integrators of rainfall over large areas, may be related to ENSO. The ability to predict flow patterns in rivers will be highly enhanced if a strong relationship between river discharge and ENSO exists, and is quantified. The stream flow forecast is vital for effective water resources management. Forecast with longer lead-times permit the reallocation of resources and the implementation of more efficient reservoir operation policies.

During the past several years, there has been considerable interest in addressing the relationship between ENSO and the variability in the stream flow at different spatial scale. Chiew and McMahon (2002) investigated global ENSO-streamflow teleconnection through fitting a first harmonic to 24-month El Nino streamflow composites from 581 catchments worldwide. The potential for forecasting is investigated by calculating the lagged correlation between streamflow and two indicators of ENSO in that study. At regional scale, the ENSO-streamflow teleconnection in United States (Redmond and Koch, 1991; Cayan et al., 1999; Piechota et al., 1997; Kahya and Dracup 1993), in Turkey (Kahya and Karabork, 2001), in Australia (Simpson et al.,1993; Chiew et al., 1998; Simpson et al., 1993) , in Sri Lank (Zubair and Chandimala, 2006; Chandimala and Zubair, 2007) and in Nepal (Shrestha and Kostaschuk, 2005) et al., have been published. At local scale, significant relationship between ENSO indicators and the streamflow have been revealed for some important river, such as Mississippi River (Twine et al., 2005), Colombia River (Gutiérrez and Dracup, 2001; Barton and Ramírez, 2004; Hamlet and Lettenmaier, 1999), Salt River Basin in Arizona (Karamouz and Zahraie, 2004) and Ganges River (Whitaker et al., 2001; Jahan et al., 2006).

In this analysis, we will look specifically at the Headwaters Region of the Yellow River (HRYR), located mainly in the Qinghai Province in western China (Fig. 1). The Yellow River is the second-longest river in China (and the sixth-longest in the world), which is called "the cradle of Chinese civilization", as its basin is the birthplace of the northern Chinese civilizations and was the most prosperous region in early Chinese history. The headwaters region of the Yellow River are most important in an international sense because they generate 40% of the flow in the whole Yellow river system, a densely-populated region with major economic, cultural and environmental significance. Although many studies have qualitatively discussed the effect of ENSO on stream flow in HRYR through analysis the runoff difference between different ENSO phases (Wang et al., 2001; Lan et al., 2002; Wang et al., 2006), it is difficult to make long range forecast based on ENSO indicators without constructing tested and quantified relationship between periodical stream flow and ENSO indicators. In this study, we will try to link the relationship between monthly discharges in HRYR and ENSO indicators and discuss the feasibility of monthly streamflow forecasting using this relationship.

In northern China, the Huanghe (Yellow River) is a major source of freshwater for about 107 million people within the river basin (Fig. 1), about 8.7% of the total population in China (Wang et al., 2006). The basin includes approximately 3.1 million hectares of irrigation area for agriculture, making up 12.5% of the total agricultural irrigation area in China.

In Sect. 2 we will describe the data and method used in the analysis. In Sect. 3, the relationship between monthly discharge and ENSO indicators will be examined. To improve our understanding, two other relationships, i.e. monthly discharge and monthly precipitation, monthly precipitation and ENSO indicators, will also be examined. In Sect. 4, the main conclusions are summarized and their implications are discussed.

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2 Data and method

2.1 Hydro climate data

The HRYR is located primarily in Qinghai Province. Minor portions of the basin extent into two surrounding provinces (Sichuan and Gansu) (see Fig. 1). Fifty years (1956–2005) of continuous monthly streamflow data (Fig. 2) for this study are taken at Tangnaihai Hydrometric Station (100.09° E, 35.30° N), from modified streamflow record database compiled by Hydrology and Water Resource Surveying Bureau of Qinghai Province. The streamflow data used here has been modified by a procedure to recover the discharges used in daily life and industrial and agricultural production in upper reach. In other words, the modified flows are used to represent the naturalized or virgin or unimpaired streamflow at a specific depletion level.

The climate data, i.e. temperature and precipitation, were taken from China Meteorological Administrator via http://cdc.cma.gov.cn/. The Figs. 3 and 4 are shown the average monthly rainfall and temperature respectively. Maximum monthly precipitation of HRYR is occurred at July. The periods from January to March and from November to December are lack of rain, averaged monthly rainfall below 20 mm. The averaged monthly temperature is above zero between April and September, and is below zero for other months.

2.2 ENSO indicators

The ENSO activity typically is monitored by observing the sea level pressures and Tropical Pacific Sea Surface Temperature (SST) in the equatorial Pacific. The ENSO indicators used in this study are the US Southern Oscillation Index (SOI) and the SSTs in three different regions (known as Niño 1.2, Niño 3, Niño 4, and Niño 3.4) (see Fig. 5).

The SOI is the most commonly used indicator to quantify the strength of an ENSO event and is computed as the normalized difference in standardized sea level pressure anomalies between Tahiti and Darwin relative to its root mean square (Troup, 1965).

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The SOI data used in this study were retrieved from the Climate Prediction Centre of National Oceanic and Atmospheric Administration (CPC, NOAA) (http://www.cpc.noaa.gov/data/indices/soi). The other indicators are the Niño 1.2, Niño 3, Niño 4, and Niño 3.4 SST anomalies in various equatorial Eastern Pacific Ocean regions: Niño 1.2 (80° W–90° W, 10° S to the Equator), Niño 3 (120° W–150° W, 5° S to 5° N), Niño 3.4 (120° W–170° W, 5° S to 5° N) and Niño 4 (150° W–180° W, 5° S to 5° N) (see Fig. 5). Data for these indicators can also be obtained from the CPC database (http://www.cpc.noaa.gov/data/indices/).

2.3 Method

In order to determine the relationship between ENSO indicators and the monthly steamflow and rainfall of HRYR, and the feasibility of using this relationship to forecast monthly water resource, following unknowns had to be determined: (1) which ENSO indicator(s) has the best correlation with each monthly streamflow and rainfall; (2) which monthly indicators has the best correlation; (3) what the lead-time or lag is for this relationship.

To determine the unknown described above, cross-correlation analysis were performed for each monthly streamflow and monthly ENSO indicator with different lag period. The Pearson correlation coefficient, which is a linear measure, was used (Press et al., 1992). A correlation was taken to be significant when the hypothesis that there was no correlation between two time-series was unlikely with a probability of 95% and highly significant when the probability was 99%. Lag-zero to lag- twelve were used, with the "*lag-n*" correlation defined as the significant correlation that can be obtained using information available *n* months before.

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3 Result

3.1 Precipitation-discharge relationships

Many studies have demonstrated that ENSO-driven precipitation fluctuations translate into significant variation of streamflow in several regions (Cayan et al., 1999; Kahya and Dracup, 1993, 1994, 1999; Kazadi, 1996; Marengo et al., 1998). Therefore, to better understand the relationship between ENSO and monthly streamflow in HRYR, the relationship between monthly precipitation and monthly discharge was examined firstly (Table 1). It is shown that discharge of January, February, and March (JFM) is mainly affected by the precipitation of June, July, August, September, and October (JJASO) of the previous year. In spring, snow is the main form of precipitation as the averaged monthly temperature is below zero (Fig. 4). In this period, base flow accounted for a majority of monthly discharge in HRYR (Liang et al., 2008). June, July and August is the rainy season of HRYR and is the important ground water recharge period (Fig. 3). With less but continuous rainfall, September and October are also valuable period for ground water recharge (Chang et al., 2007). Through the above analysis, it is show that the precipitation of JJASO in the last year affects spring discharge through altering the base flow with contributing the variation of ground water store.

In April and May, snowmelt is becoming an important component of streamflow as the averaged monthly temperature is above zero. In this period, the streamflow compose three parts, i.e. snowmelt, rainfall, and base flow. It found that streamflow in April is significantly correlated with both precipitation of August of previous year and precipitation of current year's January and February. Streamflow of May are statistically correlated with precipitation of last year's August, September, with precipitation of current year's Februry and April at 95% confidence level. In this period, last year's precipitation, i.e. in August and September, could affect the base flow through recharging the ground water. Precipitations in January and February have contributed the accumulation of snow and affect the snowmelt runoff.

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In June, streamflow are correlated with precipitation of the same month at 95% confidence level. It also has significant correlation with precipitation in April and precipitation in last year's October. It indicated that streamflow in June are affect by precipitation of current month, of previous months and base flow.

During July, August, and September (JAS), streamflow achieve the highest level over the year. Streamflow of JAS not only correlated with precipitation of current month, but also correlated with precipitation of previous one or two months. With higher intensity and more concentrated precipitation, it is easier to generate surface runoff during this period (Chang et al., 2007). The precipitation of previous 1–2 months impacts monthly streamflow main through altering the soil moisture and groundwater store.

For period October, November, and December (OND), streamflow is decreasing following significant reduction in precipitation. Base flow account for majority component of runoff of OND. Precipitation of previous months could affect runoff of OND greatly through recharging groundwater. Correlation analysis shown that streamflow of OND has significant correlation with the precipitation of July, August, September, and October at 95% confidence level.

3.2 ENSO-Precipitation relationships

Many studies have examined the teleconnection between ENSO and precipitation throughout the tropics and in broad swaths of the extratropics regions (Ropelewski and Halpert, 1987, 1989, 1996; Chiew et al., 1998; Chandimala and Zubair, 2007). In this section, using historical monthly precipitation data (1956–2005) and ENSO indicators (i.e. SOI, Niño 1.2, Niño 3, Niño 4, and Niño 3.4) data (1955–2005), the correlation between monthly precipitation of HRYR and ENSO indicators were examined (Table 2).

It was found that there are significant correlation at 95% confidence level during three periods, i.e. January and March, from September to November (Table 2). In January, lag-three and lag-nine precipitation-SOI are significantly at 95% confidence level. Both monthly Niño 3 and Niño 3.4 have significant correlations with precipitation in January with continuous lag months (Table 2). For the precipitation in March, it

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was significantly correlated with all the ENSO indicators but Niño 1.2 with different lag period from lag-zero to lag-eleven. Further analysis show that there were significant correlations with continuous lag period from short lag period to longer period for Niño 4 at 90% confidence level (Table 2).

In September, the precipitation only have correlation with Niño 3 ($r = -0.317$ with lag-seven) and Niño 1.2 ($r = -0.476$ with lag-seven and $r = -0.370$ with lag-eight) at 95% confidence level. Significant correlations with continuous lag period are found in OND. In October, the precipitations is significantly correlated with monthly SOI and Niño 3 for lag periods from zero to three months and have significant correlation with monthly Niño 4 and Niño 3.4 for lag periods from zero to four months. There is significant correlation between precipitation in November and monthly ENSO indicators for longer lag periods, i.e. from six to twelve months for Niño 3, Niño 4, and Niño 3.4; from eight to twelve months for SOI and Niño 1.2.

3.3 ENSO-discharge relationships

In this section, the relationship between monthly streamflow of HRYR and ENSO indicators were examined. It is a valuable work as significant correlation and relative longer lead time determined the feasible of predicting streamflow using ENSO indicators. There were significant correlations between monthly streamflow and monthly ENSO indictors during three periods, i.e. JFM, June, and OND, and no significant correlations were detected during other periods (Table 3).

During JFM, streamflow were positively correlated with SOI and were negatively correlated Niño 4 with different lag period at 95% confidence level. The significant correlation between streamflow in January and monthly Niño 4 was continuously significant from lag-one to lag-twelve and achieved the highest correlation efficiency ($r = -0.418$) at lag-five month. The significant streamflow-Niño 4 correlations in February was found between lag-two and lag-eight and achieved the highest correlation efficiency ($r = -0.437$) at lag-six month. For streamflow in March, it has significant correlations with Niño 4 with lag period from lag-two to lag-nine and achieved the highest

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correlation efficiency ($r = -0.448$) at lag-seven month. Further analyses shown that monthly streamflow in JFM have the strongest correlation with the Niño 4 of last autumn. Monthly streamflow in JFM were also detected having significantly correlated with periodical SOI from April to September of the last year. Correlation efficiency of streamflow-SOI in March was higher than that in January and February. Through comparing the correlation between streamflow-SOI, and streamflow-Niño 4, it was found that streamflow-Niño 4 correlation has higher correlation coefficient and longer lag period than streamflow-SOI.

In June, streamflow was negatively correlated with SOI, Niño 4, and Niño 3.4 at 95% confidence level (Table 3).Lag correlation analysis shown that streamflow in June was significantly correlated with Niño 4 for lag period from two to eleven month and earned the highest correlation efficiency ($r = -0.459$) with Niño 4 of four months before, i.e. last December. Streamflow-Niño 3.4 correlation was also detected significant between lag-three to lag-eleven month and achieved highest correlation efficiency ($r = -0.377$) at lag-eight month.

During OND, all ENSO indicators but Niño 1.2, have significant correlation with monthly streamflow. Streamflow of October was both positively correlated with monthly SOI and negatively correlated with monthly Niño 4 and Niño 3.4 at 95% confidence level for lag periods between one and three months. In other words, streamflow of October was significantly correlated with monthly SOI, Niño 4 and Niño 3.4 value of September, August, and July at 95% confidence level. Streamflow of OND was positively correlated with monthly SOI of September, August, and July at 95% confidence level (Table 3). Among these indicators, SOI have the longer lag period than others and Niño 4 have the highest correlation efficiency. From Table 3 it can also be found that streamflow in OND was significantly correlated with the monthly SOI, Niño 3, Niño 4, and Niño 3.4 of September, August, and July.

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4 Discussion

Cross-correlation analysis shows that the precipitation and runoff in headwater regions of Yellow River have significant correlation with different ENSO indicator during three periods (Tables 2 and 3), e.g. JFM, June, and ODN. For other period, e.g. April, May, July, August and September, runoff has no significant correlation with ENSO. Through comprehensively analysis precipitation-runoff (Table 1), precipitation-ENSO (Table 2), and runoff-ENSO (Table 3) correlations, it was indicated that the monthly runoff which have no significant correlation with ENSO indicators mainly due to periodical precipitation which have significantly related with monthly runoff have no significant correlation with ENSO. For example, runoff in May was significantly correlated with rainfall of February (Table 1), whereas the rainfall of February was no significant correlation with ENSO indicators (Table 2). Thus, the correlation between runoff in May and ENSO indicators was not significant at 95% confidence level.

During JFM, SOI and Niño 4 have significant correlation with runoff, while in June and October, Niño 3.4 also have significant correlation with runoff except for SOI and Niño 4. All indicators except Niño 12 were significantly correlated with monthly runoff of OND. It was indicated that using different indicator to represent ENSO activity could got different result when we try to find the relationship between runoff variation and ENSO activity. Beebee and Manga (2004) also found this difference when they examined the relationship between snowmelt runoff in Oregon and ENSO. It was also shown in Table 2 and Table 3 that these correlations have different lag periods between one and twelve months. In other words, ENSO indicator period ends one to twelve months before the streamflow period. Recent studies indicate that ENSO events can be accurately predicted one to two years in advances using physical model of coupled ocean-atmosphere system (Cane et al., 1986; Ropelewski, 1992; Chen et al., 1995; Piechota et al., 1997; Whitaker et al., 2001; Gutiérrez and Dracup, 2001). In such instances, the leading time for forecasting runoff using ENSO indicator in the Headwaters Region of the Yellow River can be extended to one to thirty-six months. Therefore, ENSO may

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have potential as a powerful forecast tool for water resource in headwater regions of Yellow River.

JFM and ODN is the dry season of headwater regions of Yellow River. The water demand of low reach region of Yellow River in dry season is more crucial than that in wet season as runoff in dry season with low discharge usually constrain the industrial and agricultural development of these regions. Therefore, forecasting capacity of JFM and ODN runoff using ENSO indicators examined in this study is very important for water management of lower reach of Yellow River.

5 Conclusions

The analyses show that rainfall during three periods, i.e. January and March, from September to November, has significant correlation with ENSO indicators at 95% confidence level with lag period from zero to twelve months. This investigation demonstrate that there were significant correlations between monthly streamflow and monthly ENSO indictors during three periods, i.e. JFM, June, and OND, and no significant correlations were detected during other periods. Lagged correlation between ENSO indicators, rainfall and runoff indicate that indicators of ENSO can be used with some success to forecast rainfall and runoff n headwater regions of Yellow River several months in advance.

Although this study establishes statistical links between El Niño-Southern Oscillation and observed streamflow in headwater regions of Yellow River, further research on the physical mechanisms driving these relationships is needed. Thus comprehensive water balance studies are required to determine the source of atmospheric moisture and precipitation as well as factors governing evapotranspiration following ENSO activities. Thus future studies are necessary to better understand the role of ENSO in the global hydrologic cycle and its potential future state using coupled atmospheric/oceanic/land surface models.

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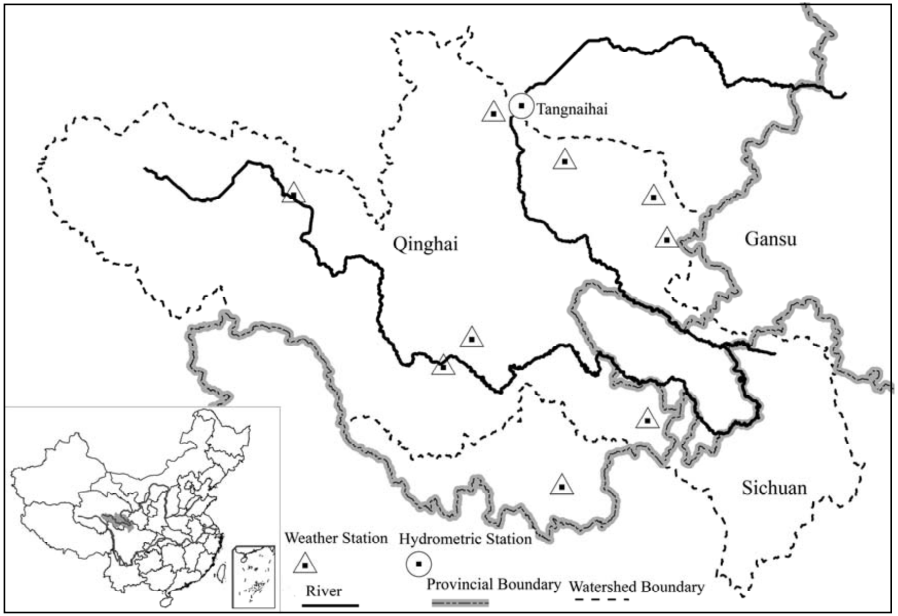

Fig. 1. The geographic location of Headwaters region of Yellow River and the location of hydrometric station used in this study.

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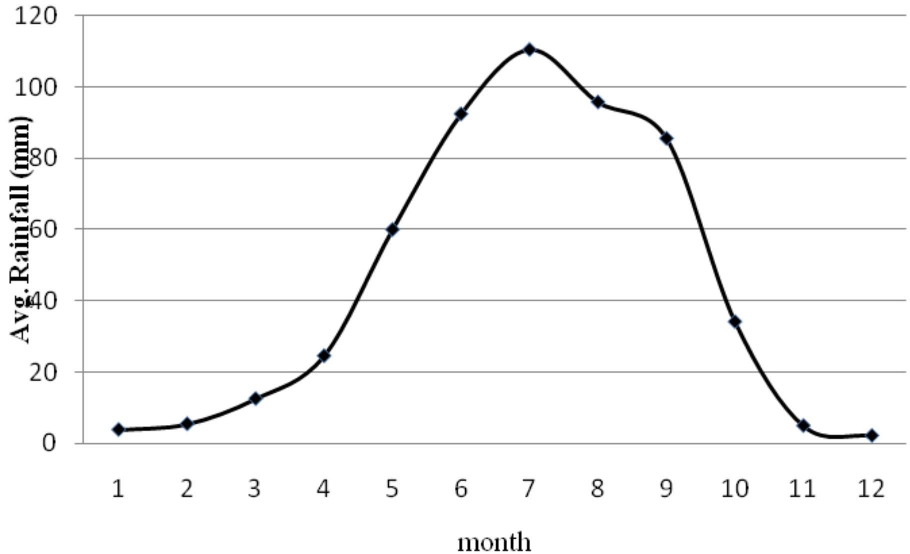

Fig. 2. Average monthly streamflow hydrographs of headwaters region of the Yellow River.

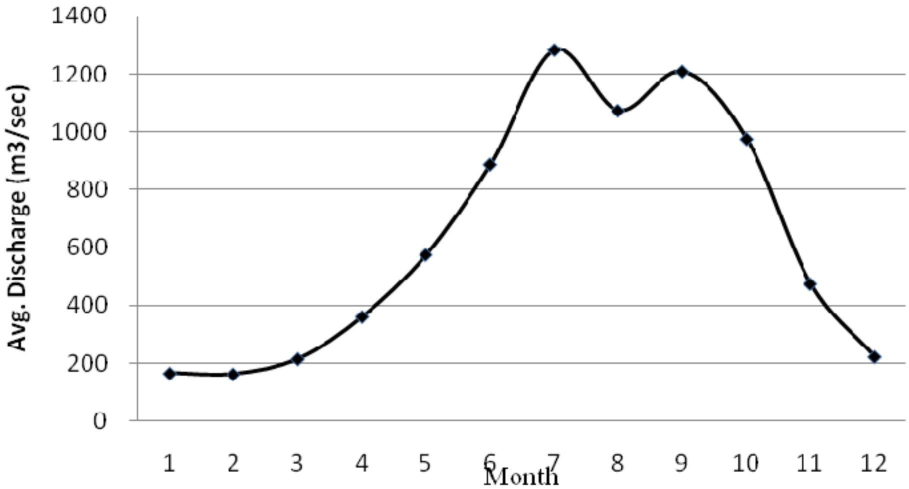

Fig. 3. Average monthly rainfall of headwaters region of the Yellow River.

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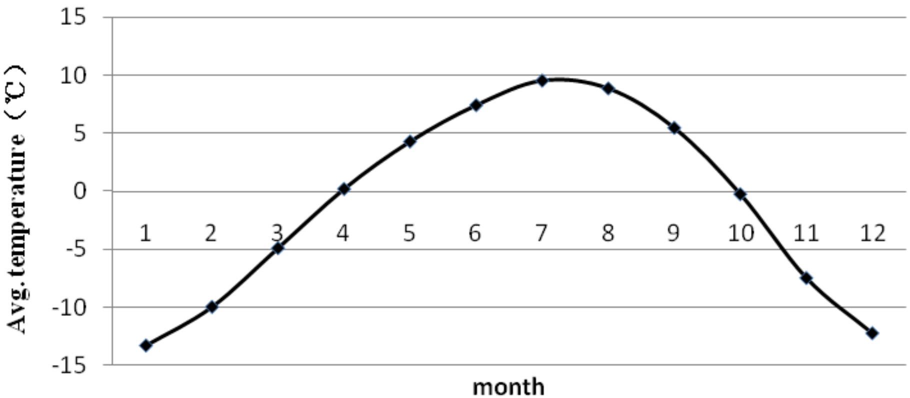

Fig. 4. Average monthly temperature of headwaters region of the Yellow River.

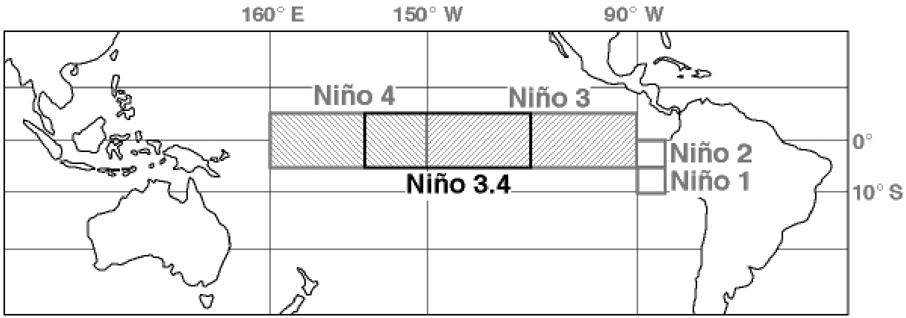

Fig. 5. SST regions (referred to Niño 1.2, Niño 3, Niño 4, and Niño 3.4) monitoring ENSO conditions.

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Table 1. The correlations between monthly runoff and monthly precipitation with different lag month.

	Lag (month)												
Month	0	1	2	3	4	5	6	7	8	9	10	11	12
Jan	0.032	−0.084	0.200	**0.294**	**0.508**	**0.428**	**0.346**	**0.305**	0.201	0.160	−0.132	−0.031	−0.042
Feb	0.069	0.047	0.000	0.138	0.289	**0.433**	**0.347**	**0.319**	**0.310**	0.205	0.199	−0.111	−0.008
Mar	−0.084	0.267	0.019	−0.155	0.156	0.257	**0.433**	**0.379**	0.273	0.218	**0.301**	0.153	−0.119
Apr	0.100	0.249	**0.314**	**0.357**	−0.204	0.127	0.110	0.194	**0.320**	0.036	0.198	0.080	−0.012
May	0.217	0.289	0.186	**0.310**	0.113	−0.149	0.120	0.033	**0.356**	**0.350**	0.114	0.051	0.154
Jun	**0.512**	0.106	**0.325**	0.014	0.193	0.091	−0.133	−0.084	**0.304**	0.109	0.144	−0.022	0.078
Jul	**0.470**	**0.591**	0.287	0.003	−0.202	0.048	−0.020	−0.069	−0.059	0.276	**0.300**	0.016	0.170
Aug	**0.400**	**0.650**	0.181	0.232	−0.145	−0.128	0.094	−0.007	−0.066	0.204	0.274	0.194	−0.109
Sep	**0.654**	**0.580**	**0.291**	0.083	0.163	0.064	−0.041	−0.222	−0.086	−0.109	0.186	−0.043	0.216
Oct	**0.437**	**0.630**	**0.346**	**0.294**	0.149	0.043	0.178	−0.064	−0.195	−0.017	0.008	0.103	−0.058
Nov	0.179	**0.564**	**0.428**	**0.411**	**0.295**	0.199	0.067	0.145	−0.046	−0.066	0.051	0.004	0.052
Dec	−0.103	0.125	**0.415**	**0.455**	**0.448**	**0.379**	0.200	0.173	0.153	−0.091	−0.027	−0.006	−0.008

Note: Significant correlation at 95% confidence level are shown with bold italic values.

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Table 2. The correlations between monthly precipitation and monthly ENSO indicators with different lag month.

Month	ENSO indicator	Lag (Month) 0	1	2	3	4	5	6	7	8	9	10	11	12
Jan	soi	−0.064	−0.010	−0.028	**−0.318**	−0.103	−0.186	−0.126	−0.284	0.016	**−0.303**	−0.259	−0.133	−0.262
	nino3	−0.034	−0.020	−0.019	−0.022	0.022	0.022	0.052	0.237	**0.421**	**0.483**	0.268	0.214	0.129
	nino4	0.025	0.055	0.066	0.063	0.179	0.158	0.243	0.238	0.218	0.228	0.186	0.130	0.120
	nino12	−0.126	−0.014	−0.005	0.061	0.055	0.069	0.079	0.159	0.238	0.253	0.200	0.236	0.146
	nino34	−0.004	−0.014	−0.005	−0.023	0.064	0.040	0.122	0.253	**0.429**	**0.448**	0.269	0.194	0.130
Mar	soi	**−0.434**	**−0.400**	−0.198	−0.285	−0.250	**−0.324**	**−0.303**	**−0.384**	−0.265	−0.204	**−0.302**	**−0.367**	−0.120
	nino3	**0.301**	0.288	0.270	**0.307**	**0.336**	**0.344**	**0.346**	0.228	0.279	**0.321**	**0.291**	0.178	0.227
	nino4	**0.316**	0.269	**0.327**	**0.346**	0.287	**0.304**	**0.361**	**0.302**	**0.355**	**0.363**	**0.365**	**0.348**	0.276
	nino12	0.085	0.255	0.236	0.219	0.257	0.292	0.180	0.087	0.128	0.177	0.156	0.156	0.194
	nino34	**0.330**	0.256	0.275	**0.318**	**0.313**	**0.323**	**0.358**	0.267	**0.317**	**0.369**	**0.342**	0.262	0.225
Sep	soi	0.161	0.234	0.168	0.117	0.150	0.243	0.181	0.138	0.083	−0.017	0.038	0.111	0.094
	nino3	−0.090	−0.116	−0.082	−0.129	−0.197	−0.234	−0.266	**−0.317**	−0.217	−0.161	−0.174	−0.135	−0.141
	nino4	−0.097	−0.077	−0.095	−0.155	−0.120	−0.145	−0.129	−0.124	−0.145	−0.104	0.009	−0.004	0.011
	nino12	−0.179	−0.199	−0.150	−0.210	−0.191	−0.101	−0.227	**−0.476**	**−0.370**	−0.308	−0.229	−0.224	−0.161
	nino34	−0.081	−0.072	−0.067	−0.146	−0.202	−0.273	−0.212	−0.226	−0.181	−0.119	−0.122	−0.075	−0.094
Oct	soi	**0.399**	**0.465**	**0.355**	**0.392**	0.115	**0.412**	**0.292**	0.010	−0.097	−0.016	0.101	0.098	−0.040
	nino3	**−0.507**	**−0.438**	**−0.311**	**−0.304**	−0.237	−0.112	−0.045	0.025	0.111	0.124	0.156	0.133	0.149
	nino4	**−0.530**	**−0.487**	**−0.466**	**−0.422**	**−0.353**	−0.285	−0.288	−0.209	−0.162	−0.124	−0.017	−0.020	0.024
	nino12	**−0.317**	−0.253	−0.136	−0.088	−0.099	−0.038	−0.094	−0.050	0.097	0.169	0.212	0.218	0.226
	nino34	**−0.550**	**−0.497**	**−0.450**	**−0.431**	**−0.362**	−0.206	−0.145	−0.055	0.004	0.041	0.088	0.083	0.134
Nov	soi	−0.047	0.041	0.122	0.086	0.075	0.069	0.080	0.262	**0.306**	**0.349**	**0.321**	**0.333**	**0.342**
	nino3	−0.019	−0.044	−0.097	−0.142	−0.173	−0.271	**−0.327**	**−0.415**	**−0.404**	**−0.401**	**−0.396**	**−0.383**	**−0.387**
	nino4	−0.071	−0.074	−0.129	−0.151	−0.208	−0.252	**−0.320**	**−0.381**	**−0.429**	**−0.418**	**−0.376**	**−0.305**	−0.262
	nino12	−0.034	−0.138	−0.178	−0.210	−0.186	−0.266	−0.237	−0.180	**−0.292**	**−0.343**	**−0.371**	**−0.410**	**−0.391**
	nino34	0.000	−0.006	−0.051	−0.049	−0.108	−0.235	**−0.352**	**−0.472**	**−0.436**	**−0.427**	**−0.396**	**−0.349**	**−0.342**
Dec	soi	**−0.291**	−0.261	−0.250	−0.190	−0.324	−0.178	**−0.328**	−0.195	−0.100	−0.038	0.324	0.103	0.119
	nino3	**0.298**	**0.305**	**0.303**	**0.306**	0.274	0.272	0.189	0.076	−0.014	−0.085	−0.110	−0.165	−0.155
	nino4	0.212	0.195	0.183	0.248	0.223	0.188	0.095	−0.045	−0.073	−0.172	−0.185	−0.152	−0.216
	nino12	**0.349**	**0.354**	**0.307**	**0.304**	0.229	0.223	0.149	0.038	0.132	0.063	−0.019	−0.070	−0.055
	nino34	0.234	0.247	0.243	**0.302**	0.285	0.250	0.150	0.024	−0.123	−0.171	−0.185	−0.195	−0.214

Note: Significant correlation at 95% confidence level are shown with bold italic values.

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Table 3. The correlations between monthly streamflow and monthly ENSO indicators with different lag month.

Month	ENSO indicator	Lag (Month) 1	2	3	4	5	6	7	8	9	10	11	12
Jan	soi	0.066	−0.019	0.126	**0.284**	**0.297**	**0.276**	0.256	**0.346**	**0.289**	0.049	0.121	−0.006
	nino3	−0.178	−0.203	−0.222	−0.133	−0.076	−0.059	−0.065	−0.102	−0.087	−0.170	−0.112	−0.090
	nino4	**−0.277**	**−0.326**	**−0.334**	**−0.399**	**−0.418**	**−0.371**	**−0.327**	−0.270	**−0.304**	−0.240	**−0.282**	**−0.310**
	nino12	−0.107	−0.134	−0.154	−0.019	0.077	0.115	0.025	−0.039	0.019	−0.088	−0.081	−0.037
	nino34	−0.204	−0.235	−0.261	−0.227	−0.206	−0.216	−0.217	−0.193	−0.216	−0.177	−0.161	−0.156
Feb	soi	−0.122	0.068	0.047	0.156	**0.344**	**0.305**	**0.280**	0.256	**0.323**	0.233	−0.044	0.028
	nino3	0.031	−0.203	−0.217	−0.235	−0.130	−0.073	−0.043	−0.023	−0.003	0.050	−0.034	0.029
	nino4	−0.248	**−0.335**	**−0.384**	**−0.391**	**−0.417**	**−0.437**	**−0.380**	**−0.306**	−0.261	**−0.279**	−0.197	−0.220
	nino12	0.133	−0.109	−0.142	−0.136	0.012	0.131	0.175	0.113	0.065	0.155	0.047	0.076
	nino34	−0.054	−0.253	−0.276	−0.305	−0.251	−0.232	−0.236	−0.202	−0.120	−0.133	−0.082	−0.048
Mar	soi	0.183	0.181	0.113	0.085	0.200	**0.379**	**0.356**	0.264	0.266	**0.335**	0.190	0.075
	nino3	−0.194	−0.237	−0.253	−0.259	−0.264	−0.139	−0.087	−0.077	−0.083	−0.066	−0.011	−0.029
	nino4	−0.270	**−0.310**	**−0.331**	**−0.391**	**−0.393**	**−0.436**	**−0.448**	**−0.391**	**−0.311**	−0.243	−0.230	−0.125
	nino12	−0.124	−0.115	−0.184	−0.197	−0.176	−0.041	0.077	0.149	0.078	0.049	0.102	0.000
	nino34	−0.213	−0.266	−0.277	−0.298	−0.314	−0.248	−0.238	−0.248	−0.236	−0.165	−0.134	−0.034
Jun	soi	0.170	0.239	0.123	0.099	0.308	0.171	0.222	0.211	0.346	0.321	0.272	0.126
	nino3	−0.029	−0.123	−0.195	−0.166	−0.241	−0.264	−0.273	**−0.316**	−0.250	−0.252	−0.245	−0.167
	nino4	−0.252	**−0.357**	**−0.395**	**−0.459**	**−0.449**	**−0.398**	**−0.424**	**−0.401**	**−0.317**	**−0.372**	**−0.297**	−0.142
	nino12	−0.069	−0.011	0.005	0.040	−0.082	−0.160	−0.185	−0.193	−0.159	−0.072	−0.012	0.005
	nino34	−0.150	−0.281	**−0.292**	**−0.316**	**−0.349**	**−0.332**	**−0.350**	**−0.377**	**−0.292**	**−0.348**	**−0.347**	−0.240
Oct	soi	**0.384**	**0.358**	**0.290**	0.255	0.277	0.243	0.004	−0.103	−0.090	−0.072	−0.190	−0.096
	nino3	−0.233	−0.167	−0.146	−0.087	−0.066	0.004	−0.022	0.029	0.107	0.163	0.133	0.155
	nino4	**−0.426**	**−0.405**	**−0.333**	−0.236	−0.174	−0.176	−0.055	−0.063	−0.077	−0.015	0.033	0.058
	nino12	−0.144	−0.040	0.012	−0.035	−0.038	−0.033	−0.142	−0.108	0.066	0.093	0.140	0.088
	nino34	**−0.320**	**−0.293**	**−0.296**	−0.225	−0.146	−0.101	−0.005	0.013	0.052	0.116	0.095	0.147
Nov	soi	0.250	**0.447**	**0.396**	**0.389**	**0.310**	**0.344**	**0.281**	0.008	−0.074	−0.050	−0.007	−0.150
	nino3	**−0.403**	**−0.303**	−0.219	−0.201	−0.136	−0.103	−0.033	−0.031	0.055	0.101	0.149	0.115
	nino4	**−0.489**	**−0.511**	**−0.499**	**−0.431**	**−0.307**	−0.241	−0.257	−0.124	−0.128	−0.143	−0.062	−0.043
	nino12	−0.291	−0.167	−0.046	0.013	−0.031	−0.043	−0.035	−0.117	−0.005	0.112	0.121	0.166
	nino34	**−0.453**	**−0.403**	**−0.366**	**−0.372**	**−0.288**	−0.194	−0.153	−0.045	−0.004	0.022	0.082	0.056
Dec	soi	0.056	0.210	**0.388**	**0.354**	**0.396**	**0.330**	**0.339**	**0.295**	0.018	−0.037	−0.016	−0.025
	nino3	**−0.311**	**−0.337**	−0.240	−0.181	−0.147	−0.141	−0.154	−0.084	−0.094	0.002	0.046	0.097
	nino4	**−0.430**	**−0.418**	**−0.453**	**−0.456**	**−0.401**	**−0.309**	−0.262	**−0.276**	−0.139	−0.148	−0.167	−0.101
	nino12	−0.220	−0.253	−0.108	−0.011	0.028	−0.051	−0.104	−0.063	−0.146	−0.036	0.091	0.093
	nino34	**−0.364**	**−0.391**	**−0.344**	**−0.322**	**−0.315**	**−0.285**	−0.232	−0.200	−0.087	−0.046	−0.029	0.033

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