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Runoff-denoted drought index and its relationship to the yields of spring wheat in the arid area of Hexi corridor, Northwest China

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ABSTRACT

A drought index is defined based on the inland river runoff from Hexi corridor, Gansu Province, Northwest China. The relationship between this drought index and yields of spring wheat is examined. The data used in this study include the following: monthly runoff data during 1959–2004 from the hydrological stations at Changmapu, Yingluoxia and Jiutiaoling on the three representative inland rivers in the Hexi corridor belt; the yields of spring wheat, monthly temperature and precipitation from three agro-meteorological stations in Jiuquan, Zhangye and Wuwei; and monthly precipitation data from three meteorological stations at Tole, Qilian and Menyuan.

The runoff, following the Pearson type III distribution, is normalized to translate into the standard normal distribution as function of Z. Z is the variable in normalizing process. According to the characteristic of standard normal distribution of Z, a runoff-denoted drought index (Z_{rd} hereafter) is defined. The grades of Z_{rd} are determined by the standard normal distribution theoretical frequencies of Z. In order to validate the drought grades, runoff drought indices are compared with the atmospheric dryness indices determined by the precipitation. Results indicate that the division of drought categories based on runoff is rational and thus reliable. The Z_{rd}, as it considers both temperature and rainfall in upstream mountains, is close to reality.

Based on the relationship between the drought grade and water usage, suggestions are made for irrigation in the area. Five grades of Z_{rd} are then translated into 4 grades of runoff irrigation drought index (Z_{ir}). The relationship between Z_{ir} and tendency-free yield (i.e. climate yield) of spring wheat from the Hexi Corridor irrigation zones at station Jiuquan, Zhangye and Wuwei is investigated. Results show that the Z_{ir} represents an anti-phase trend of the climate yields of the crops. As a conclusion, Z_{ir} can be utilized to qualitatively predict the trend of the wheat yield. An empirical yield model is created using a multi-variable regression method.

1. Introduction

Northwest China, an arid region, is interspersed with many oases in the wide areas of desert and Gobi (Cheng et al., 1999). Hexi corridor is one of the oases. It is also a principal base of economic crops for Gansu Province, although the area receives only 100–150 mm of rainfall yearly on average and this total rainfall is only 30% of the mean annual rainfall over the entire of the Province. The Hexi corridor is far short of water for agricultural purposes compared with the other regions of the

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Province. It is impossible to grow crops based on the natural precipitation only. Therefore, the main water resources for agriculture are from inland rivers. Thus, Hexi corridor becomes an irrigation agricultural area.

Previous studies have showed that water and fertilizer are the major factors that affect the crop production (Zhou et al., 2007; Jia et al., 2005; Stone et al., 1996). Considering the little rainfall in an ordinary year at Hexi corridor, water provided by irrigation, rather than precipitation, is a determining factor for the farmland in this area. The irrigated areas in this region depend strongly upon the runoff from the Shule, Hei and Shiyang inland rivers. The importance of irrigation maybe described as ‘‘With water in them, oases are seen in many places, while with no water inside, deserts come into view.’’ Consequently, water resources of these inland rivers are crucial to the agriculture in Hexi corridor. The drought in the irrigation areas is determined by the amount of the river runoff.

It is well known that drought is frequently described in terms of drought indices, which are convenient and relatively simple to use (Trnka et al., 2003). Considering the severity of drought in Hexi corridor mainly depends on runoff, quantitative description of drought in this area is formulated according to runoff-denoted drought index.

Studies in variations of the runoff have been done by Hu (1988) and Yuan and Sang (1998). The results indicated that the precipitation over the Qilian Mountains is a determinant of the runoff in three rivers, and mean temperature acts as a secondary element for providing additional water from melted alpine snow and ice. Matsunaka et al. (1992) has pointed out that optimum irrigation can lead to a greater yield of the spring wheat. In order to determine whether runoff is a useful indicator for designing irrigation water usage and find its relationship with spring wheat yield in this arid area, it is necessary to define a drought index using runoff and give its quantitative standard gauge classification. Based on the quantitative level of the runoff-denoted index, the degree of drought in irrigation areas can be presented.

Numerous studies have been published on the development and applications of drought indices, including Thornthwaite wet/dry Index (Thornthwaite, 1948), Antecedent Precipitation Index–API (Waggoner and O'Connell, 1956), Palmer Drought Severity Index–PDSI (Palmer, 1965), Surface Water Supply Index–SWSI (Shafer and Dezman, 1982; Kemal et al., 2005), Flood/Drought Index in North China (Ju et al., 1997; Zhang, 1998; Zhang et al., 1998). Among these studies the PDSI is most widely applied. The PDSI products have been published on an official US website since the 1960s. In addition, the PDSI is widely used in drought assessment, comparison and its spatial/temporal distributions (An and Xing, 1985; Guttman, 1998; Dai et al., 1998; Zavareh, 1999; Makra et al., 2002; Miroslav et al., 2003). However, all aforementioned drought indices are constructed based on precipitation, thus they are inapplicable to apply for Hexi corridor since the annual rainfall is quite low in the area. Up to now, little progress has been made to denote the drought indices using runoff. Therefore, establishing a runoff-dependent drought index is of practical significance to the region.

The objective of this paper is to develop a method to define the irrigation levels at Hexi Corridor region based on the drought grade obtained from inland river runoff and the relationship between drought grade and spring wheat yield. Since May to June is tasselling and milking stages of spring wheat in the arid region, and the water availability has very important influence on the growth of crop and the formation of grain yield, runoff during the key period from May to June is selected for the analysis.

The paper is organized as follows. Section 2 introduces the observational data and the methods used to process the data. Section 3 presents detailed tables and graphs of the results for runoff change, runoff-denoted drought index, and a multiple regression yield equation. The conclusions and discussion are addressed in Section 4.

2. Data and methods

2.1. *Description of Hexi corridor*

Hexi corridor, a panhandle arid region, is located between 90°21′–104°05′E and 37°15′–41°30′N at the Gansu Province in Northwest China. With the length of more than 1000 km, average width of 270 km and altitude ranging from 1000 to 1500m, it stretches from the Wushaoling (37°12′N, 102 °52′E) in the east to the Dunhuang (40°09′N, 94 °41′E) in the west, the Qilian Mountains to the south and the Mazong, Heli and Longshou Mountains to the north. With very little precipitation, strong pan-evaporation, large annual and daily variability of temperature, climate in Hexi corridor is in typical continental type. The area includes three typical hydrological stations: Changmapu(39°39′N, 96 °51′E), located in the reach of the Shule river at the west, Yingluoxia(38°14′N, 100°11′E) in the Hei river valley at the middle, and Jiutiaoling(37°52′N, 102°03′E), situated in the Shiyang catchment's area at the east of the Qilian Mountains. Three representative stations of wheat yield are Jiuquan (39°46′N, 98°29′E), Zhangye (38°56′N, 100°26′E) and Wuwei (37°55′N, 102°40′E) in the irrigation zones, each of these three stations is related to one of the three river basins, respectively (Fig. 1).

2.2. *Data*

Data sets used in this study are the monthly average runoff data from 3 hydrological stations (Changmapu, Yingluoxia and Jiutiaoling), annual per-unit yields of spring wheat, temperature, precipitation from 3 agro-meteorological stations (Jiuquan, Zhangye and Wuwei), and monthly precipitation data from 3 meteorological stations: Tole (38°48′N, 98 25′E), Qilian (38°11′N, 100°15′E) and Menyuan (37°23′N, 101°37′E). Based on the availability of the data, we use the data during 1959–2004 in this study.

2.3. *Data processing methods*

2.3.1. *Normalization of runoff*

Generally speaking, runoff in an area does not follow the standard normal distribution. It usually follows the Pearson type III distribution (Tu et al., 1984). In order to prove this hypothesis, thereinafter, we use runoff data from May to June from three representative hydrological stations to fit Pearson type III distribution. For the sake of simpleness, detailed results are presented only by using the runoff data at Changmapu hydrological station, and give its fitting curve at the same time.

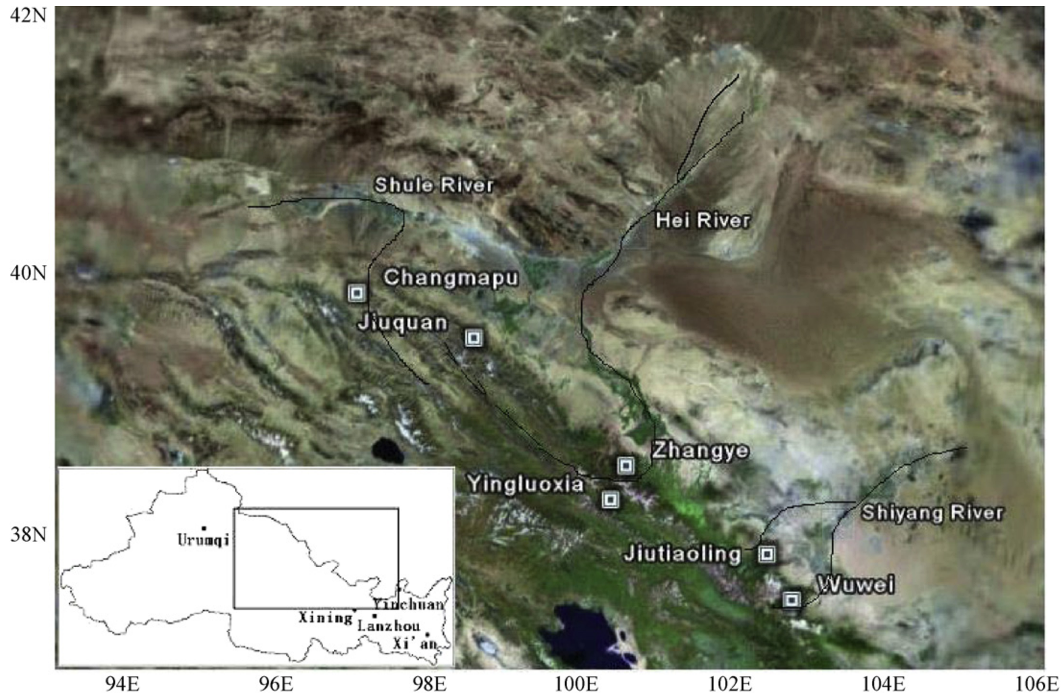

Fig. 1 – Location map of Shule, Hei and Shiyang River, and the typical hydrological measurements stations (Changmapu, Yingluoxia and Jiutiaoling) and corresponding wheat-yields stations (Jiuquan, Zhangye and Wuwei).

For the other two hydrological stations (Yingluoxia and Jiutiaoling), the fitting curves to Pearson type III distribution are provided but the detailed calculating processes are not shown. The step by step computing procedure as follows:

The ensemble average ($\bar{x}$), coefficient of variation (c_v) and skewness coefficient (c_s) of runoff data at Changmapu from 1959 to 2004 are calculated by moments method (Greenwood et al., 1979), the interim results are shown in Table 1. Then, according to Table 1

$$\bar{x} = 1.56 \times 10^8 \ \text{m}^3 \tag{1}$$

$$c_v = \sqrt{\frac{1}{n-1}\sum_{m=1}^{n}(K_m - 1)^2} = \sqrt{\frac{1}{46-1} \times 2.6} = 0.24 \tag{2}$$

$$c_s = \frac{\sum_{m=1}^{n}(K_m - 1)^3}{(n-3)c_v^3} = \frac{0.185}{(46-3) \times 0.24^3} = 0.31 \tag{3}$$

In Eqs. (2) and (3), $K_m = x_m/\bar{x}$, x_m denotes the runoff volume in different years. The curve of theoretic probability, according to the value of c_s, the P (probability) and corresponding Φ_p (coefficient of deviation from average), can be obtained by looking a table of ‘‘Pearson type III deviation coefficient’’. The values are listed in Table 2, then, x_p can be obtained by using the following formulation:

$$x_p = m(\Phi c_v + 1) \tag{4}$$

where m denotes the mathematical expectation of the runoff from May to June.

Taking x_p as ordinate and P as abscissa, a smooth curve can be obtained by linking the theoretic points of (P, x_p), and this makes a Pearson type III distribution curve of the theoretic probability with $\bar{x} = 1.56 \times 10^8$, $c_v = 0.24$ and $c_s = 0.31$ (Fig. 2a).

Then, empirical probability points are stippled from the data of the second and third columns of Table 1 as ordinate and abscissa respectively, i.e. plotting (P, x) points on Fig. 2a.

Last, eyeballing the fitting degree between empirical points and theoretic curve, if it has good fitting effect, then the theoretic curve (including curve types and estimated parameters) can be taken as bulk distribution.

It is apparently from Fig. 2a that there is good fitting effect between observed values and theoretic curve, indicating the runoff at Changmapu hydrological station from May to June obeys the Pearson type III distribution. Using the same calculation steps mentioned above, two other fitting curves are obtained (Fig. 2b and c). It can be seen from Fig. 2b and c that the empirical points and theoretic curves agree well in these two hydrological stations, respectively. Namely, runoff of three inland rivers from May to June obeys the Pearson type III distribution. A probability density function can be expressed as

$$f(x) = \frac{\beta^\alpha}{\Gamma(\alpha)}(x - a_0)^{\alpha-1}e^{-\beta(x-a_0)}, \qquad x \geq a_0, \alpha > 0 \tag{5}$$

where a_0 is the minimum value of random variable x. α and β are parameters, $\alpha = 4/c_s^2$, $\beta = 2/mc_v c_s$ $\Gamma(\alpha)$ denotes Γ function:

$$\Gamma(\alpha) = \int_0^\infty x^{\alpha-1}e^{-x}\,dx \tag{6}$$

According to the algorithm of reference (Kife, 1978), normalizing runoff would convert the probability density

Table 1 – The runoff data of Changmapu hydrological station from May to June (x_m) according to the sequence from the maximum to the minimum, the probability (P_m), and other parameters concern with calculating coefficient of variation (c_v) and skewness coefficient (c_s).

Serial number	$x_m/10^8$ (m^3)	$P_m = m/n + 1 \times 100$ (%)	$K_m = x_m/\bar{x}$	$K_m - 1$	$(K_m - 1)^2$	$(K_m - 1)^3$
1	2.442	2.128	1.565	0.565	0.320	0.181
2	2.295	4.255	1.471	0.471	0.222	0.105
3	2.245	6.383	1.439	0.439	0.193	0.085
4	2.233	8.511	1.431	0.431	0.186	0.080
5	2.148	10.638	1.377	0.377	0.142	0.054
6	2.016	12.766	1.292	0.292	0.085	0.025
7	1.925	14.894	1.234	0.234	0.055	0.013
8	1.900	17.021	1.218	0.218	0.048	0.010
9	1.878	19.149	1.204	0.204	0.042	0.008
10	1.868	21.277	1.197	0.197	0.039	0.008
11	1.830	23.404	1.173	0.173	0.030	0.005
12	1.754	25.532	1.124	0.124	0.015	0.002
13	1.751	27.660	1.123	0.123	0.015	0.002
14	1.738	29.787	1.114	0.114	0.013	0.001
15	1.735	31.915	1.112	0.112	0.013	0.001
16	1.657	34.043	1.062	0.062	0.004	0.000
17	1.649	36.170	1.057	0.057	0.003	0.000
18	1.643	38.298	1.053	0.053	0.003	0.000
19	1.614	40.426	1.034	0.034	0.001	0.000
20	1.587	42.553	1.017	0.017	0.000	0.000
21	1.555	44.681	0.997	−0.003	0.000	0.000
22	1.555	46.809	0.997	−0.003	0.000	0.000
23	1.537	48.936	0.985	−0.015	0.000	0.000
24	1.530	51.064	0.981	−0.019	0.000	0.000
25	1.502	53.191	0.963	−0.037	0.001	0.000
26	1.491	55.319	0.956	−0.044	0.002	0.000
27	1.469	57.447	0.942	−0.058	0.003	0.000
28	1.445	59.574	0.926	−0.074	0.005	0.000
29	1.444	61.702	0.925	−0.075	0.006	0.000
30	1.426	63.830	0.914	−0.086	0.007	−0.001
31	1.407	65.957	0.902	−0.098	0.010	−0.001
32	1.401	68.085	0.898	−0.102	0.010	−0.001
33	1.352	70.213	0.867	−0.133	0.018	−0.002
34	1.351	72.340	0.866	−0.134	0.018	−0.002
35	1.327	74.468	0.851	−0.149	0.022	−0.003
36	1.264	76.596	0.810	−0.190	0.036	−0.007
37	1.224	78.723	0.785	−0.215	0.046	−0.010
38	1.213	80.851	0.778	−0.222	0.049	−0.011
39	1.205	82.979	0.772	−0.228	0.052	−0.012
40	1.183	85.106	0.758	−0.242	0.058	−0.014
41	1.168	87.234	0.748	−0.252	0.063	−0.016
42	1.094	89.362	0.701	−0.299	0.089	−0.027
43	1.076	91.489	0.690	−0.310	0.096	−0.030
44	0.948	93.617	0.608	−0.392	0.154	−0.060
45	0.898	95.745	0.575	−0.425	0.180	−0.077
46	0.790	97.872	0.506	−0.494	0.244	−0.120
Sum	71.763				2.600	0.185
Average	1.560				0.057	

function of Pearson type III distribution into the standard normal distribution as function of Z. The conversion takes the form of

$$Z_i = \frac{6}{C_s}\left(\frac{C_s}{2}J_i + 1\right)^{1/3} - \frac{6}{C_s} + \frac{C_s}{6} \tag{7}$$

where C_s stands for the skewness coefficient and J_i for the variable for standardized runoff, and both can be obtained by runoff data via the following expression:

$$C_s = \frac{\sum_{i=1}^{n}(X_i - \bar{X})^3}{nS^3}, \quad J_i = \frac{X_i - \bar{X}}{S} \tag{8}$$

where S is a mean-square deviation, taking the form of $S = \sqrt{1/n\sum_{i=1}^{n}(X_i - \bar{X})^2}$.

2.3.2. *Trend-free yield of spring wheat*

An actual yield of a crop can be divided into three parts: a trend, a climate and a random component. It can be expressed as the following equation:

$$y = y_t + y_w + y_e \tag{9}$$

where y is an actual yield of crop, y_t a trend yield, y_w a climate yield and y_e a random yield. The trend yield refers to

Table 2 – The P (probability) and corresponding Φ_p (coefficient of deviation from average) obtained from the table of "Pearson III distribution curve of coefficient of deviation from average" by using the value of c_s (skewness coefficient). $x_p = m(\Phi c_v + 1)$ denotes the theoretic value of runoff, and m denotes the mathematical expectation.

P (%)	Φ ($c_s = 0.31$)	$\Phi c_v, c_v = 0.24$	$\Phi c_v + 1$	x_p
0.1	3.52	0.84	1.84	2.88
0.2	3.24	0.78	1.78	2.77
0.5	2.86	0.69	1.69	2.63
1	2.54	0.61	1.61	2.51
2	2.21	0.53	1.53	2.39
3	2	0.48	1.48	2.31
5	1.73	0.42	1.42	2.21
10	1.31	0.31	1.31	2.05
20	0.82	0.20	1.20	1.87
25	0.64	0.15	1.15	1.80
30	0.43	0.10	1.10	1.72
40	0.2	0.05	1.05	1.63
50	−0.05	−0.01	0.99	1.54
60	−0.3	−0.07	0.93	1.45
70	−0.56	−0.13	0.87	1.35
75	−0.7	−0.17	0.83	1.30
80	−0.85	−0.20	0.80	1.24
85	−1.03	−0.25	0.75	1.17
90	−1.24	−0.30	0.70	1.10
95	−1.55	−0.37	0.63	0.98
97	−1.75	−0.42	0.58	0.90
99	−2.1	−0.50	0.50	0.77
99.9	−2.64	−0.63	0.37	0.57

the portion that is resulted from non-natural elements, such as the improvement of the agricultural technology under the normal natural meteorological conditions. The climate yield denotes the component subject to the variation in climate factors; the random yield means the part under the effect of social instability, and it can be ignored because it is almost negligible for the cases studied in this paper. Then, the above equation of actual yield of a crop can be expressed as

$$y = y_t + y_w \tag{10}$$

In the actual yields records, the trend component can be removed from the actual yield. Note that the trend yield is extracted by means of a linear simulation (Feng, 1983). The detailed information of linear simulation is as follows.

Suppose that the actual yield series of crop is a linear function of time series, using the value of linear function of time series to fit the trend yield. We obtained an equation:

$$\hat{y}_t = a + b(t - \bar{t}) \tag{11}$$

where $\hat{y}_t$ is the tth theoretic value of trend yield, a is a nodal increment, b regression coefficient, t time variation, $\bar{t}$ the average of time variation t. Then

$$y_w = y - \hat{y}_t \tag{12}$$

The y_w represents climate yield, which is associated with the climate changes.

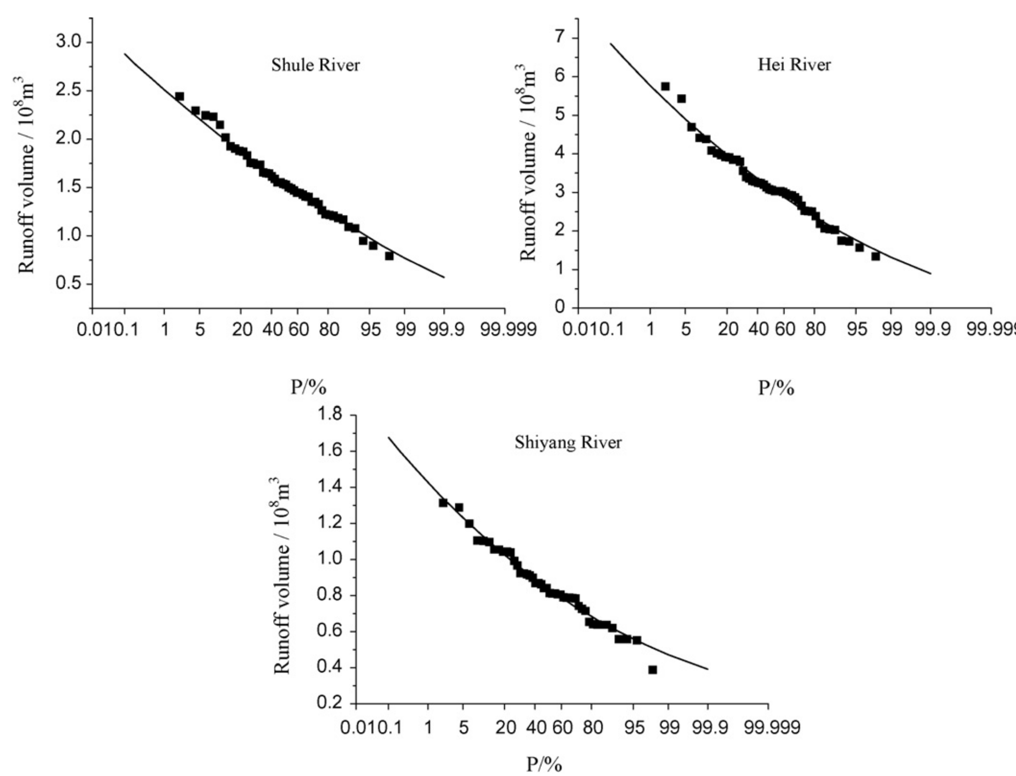

Fig. 2 – The fitting results of Pearson III type distribution for runoff in different inland rivers over Hexi corridor; solid line denotes theoretic probability curve, and solid square denotes observed value (i.e. experience point).

2.4. Multiple regression methods

Regression analysis is a commonly used statistical method. It has been used to explain or predict the behavior of a dependent variable (y). Commonly, a regression takes the form of $\hat{y} = a + bx + c$, where $\hat{y}$ is a estimate variable that the equation tries to predict. x is the independent variable that is being used to predict $\hat{y}$. a and b are the regression coefficients, and c is a value called the regression residual. The values of a and b are selected so that the square of regression residual is minimized. However, in practice, it is difficult to find a good relationship between a single independent variable (x) and a dependent variable (y). A dependent variable is usually affected by multi-variables rather than a single factor. For example, suppose there are p influencing factors, which are denoted as $x_1, x_2, \ldots, x_p$, then the multi-variate regression equation can be written as $\hat{y} = b_0 + b_1x_1 + b_2x_2 + \ldots + b_px_p$, where $b_0, b_1, \ldots, b_p$ are the regression coefficients. The correlation between the dependent variable (y) and estimate variable ($\hat{y}$) is called multiple correlation coefficient (R), which is used to assess the quality of multi-variate regression equation. In order to check the significance of the multi-variate regression equation, it is necessary to take a statistical test, for instance, the F-test. At the significance level of α, it is considered that the multi-variate regression equation is significant when the F value is bigger than the threshold F_α.

In this paper, multi-variate regression method is used to construct the regression equation between wheat yield and influencing factors. For the multi-variate regression analysis, the stepwise regression method with F values of 2, 3 and 2.5 were used for the entry of variables at Jiuquan, Zhangye and Wuwei stations, respectively. Detailed application of regression analysis can be referred from Draper and Smith (1981).

3. Results

3.1. Annual variation of runoff

As mentioned above, May to June is the key period of water use in Hexi corridor. For convenience, we shall discuss the problem in terms of the runoff during May to June. The categories of runoff are separated into 5 according to their percentage anomalies (Table 3), which are denoted by digits −2, −1, 0, +1 and +2, where digit −2 refers to the anomaly percent $\Delta < -30\%$ for a low-runoff year, digit −1 refers to $-30\% \le \Delta < -10\%$ for a relatively lower-runoff year; digit 0 represents $-10\% \le \Delta < 10\%$ for a year of normal runoff; digit +1 denotes $10\% \le \Delta$ 30% for a relatively higher-runoff year; digit +2 refers to $\Delta > 30\%$ for a high-runoff year.

On the other hand, it is obviously from Table 3 that the number of normal-runoff years accounts for 37.7%. The number of years of −2 and −1 exceeds that of years of +2 and +1 in terms of the runoff categories of three inland rivers over 1959–2004. Also, it is found that the number of −1 years is more compared to that of −2 years in the low-level runoff years and the number of +1 years is greater than that of +2 years in the runoff-plentiful years. Viewed from the sequences of runoff anomalies from three rivers, there are roughly 14.5% and 9.4% of −2 and +2 years, respectively. On average, considering the numbers of −1 and +1 years that constitute 22.5% and 15.9%. This means that the strong severity of drought and flood would happen at the low frequency.

3.2. Runoff-denoted drought index and its categories

From the foregoing analysis of the runoff variation of the three rivers, it is apparent that there are common features of low- and high-level runoffs to the three rivers. Therefore, we develop a set of standards for classifying runoff levels (water deficiency or abundance) in the rivers to indicate the associated drought/flood categories.

According to the properties of a normal distribution of variable Z described in Section 2.3.1, the Z values are divided into 5 levels and delimit their corresponding bounded domains as the drought index of each category, given in Table 4.

In Table 5 we present Z indices-determined drought/flood categories and their frequencies using 1959–2004 runoff data over the three rivers based upon Table 4–given flood/drought categories.

Compared Table 4 with Table 5, the mean frequency of flood/drought and Z category is well corresponded each other, i.e., about 40% fall into category 3 (normal), 25% fall into categories 2 (light flood) and 4 (light drought), and 5% fall into categories 1 (flood) and 5 (drought). The results are coincident with the theoretical frequencies (Table 4) and in conformity with reality.

3.3. Drought/flood grades from runoff-denoted drought indices in comparison to those from atmospheric drought indices

To illustrate the reasonability of the flood/drought grades from runoff drought indices presented above, we compare them with those from atmospheric drought indices, which derived

Table 3 – The runoff anomaly categories based on their anomaly percent and the low/high-runoff situation for Shule, Hei and Shiyang Rivers during 1959–2004.

Runoff anomaly percent, Δ	Corresponding category	Runoff status	Percent of different categories at three rivers (%)			Mean percent of different categories of three rivers (%)
			Shule	Hei	Shiyang	
$\Delta < -30\%$	−2	Low	13.0	15.2	15.2	14.5
$-30\% \le \Delta \le -10\%$	−1	Lower	21.7	19.6	26.1	22.5
$-10\% \le \Delta < 10\%$	0	Normal	41.3	36.9	34.7	37.7
$10\% \le \Delta < 30\%$	1	Higher	15.2	17.4	15.2	15.9
$\Delta > 30\%$	2	High	8.7	10.9	8.7	9.4

Table 4 – Z index denoted drought or flood grades for the three rivers.*.

Category	AF	Z value	D/F	TFD
1	>95%	$Z > 1.6448$	Flood	5%
2	70%–95%	$0.5244 < Z \leq 1.6448$	Light flood	25%
3	30%–70%	$-0.5244 \leq Z \leq 0.5244$	Normal	40%
4	5%–30%	$-1.6448 \leq Z < -0.5244$	Light drought	25%
5	<5%	$Z < -1.6448$	Drought	5%

* AF = accumulation frequency, D/F = drought or flood, and TFD = theoretical frequency distribution.

Table 5 – The mean percentage frequency of Z indices-shown flood/drought events for the Shule, Hei and Shiyang Rivers during 1959–2004.*.

Category	D/F	Events			MFD
		Shule	Hei	Shiyang	
1	Flood	4	2	3	6.5%
2	Light flood	10	13	12	25.4%
3	Normal	19	19	17	39.9%
4	Light drought	11	10	12	23.9%
5	Drought	2	2	2	4.3%

* D/F = drought or flood, and MFD = mean frequency distribution.

from rainfall measurements during 1959–2004 at the stations of Tole, Qilian and Menyuan, located upstream of the Shule, Hei and Shiyang River, respectively. Atmospheric drought indices were cited from Zhang et al. (1998). The results are shown in Table 6, which gives seven drought/flood levels. These levels are corresponding with the 5 levels of drought indices in Table 5. Specifically, grades 2 and 3 (5 and 6) of drought/flood levels are combined to denote "light flood" ("light drought"), followed by rewriting the "severe flood" and "severe drought" in Table 7 as "flood" and "drought", leading to the fact that the "normal" grade represented by atmospheric dryness index forms on the order of 40%. The "light flood" and "light drought" grades each constitutes about 25% of the total frequency. The "flood" and "drought" grades each account for about 5% of the total frequency. This distribution of frequencies of flood/drought events given by atmospheric drought indices is roughly similar to those from runoff-produced categories (Table 5). Consequently, the division of flood/drought categories based on runoff is rational and thus reliable.

Table 6 – Distribution of mean frequencies for atmospheric dryness indices-denoted flood/drought grades from rainfalls measured at stations upstream of the respective rivers during 1959–2004.*.

Category	D/F	Events			MFD
		Tole	Qilian	Menyuan	
1	Severe flood	3	2	2	5.1%
2	Heavy flood	4	6	7	12.3%
3	Light flood	6	6	5	11.6%
4	Normal	18	19	17	40.9%
5	Light drought	6	7	9	15.9%
6	Heavy drought	6	5	4	11.4%
7	Severe drought	3	1	2	4.6%

* D/F = drought or flood, and MFD = mean frequency distribution.

Based on Tables 5 and 7, further comparison is made for the frequencies of runoff-denoted flood/drought grades at three hydrological stations with those of atmospheric drought indices grades at stations Tole, Qilian and Menyuan, upstream of Changmapu, Yingluoxia and Jiutiaoling in the Shule, Hei and Shiyang basins. It is found that the "normal" category from the Shule runoff is higher in frequency than that given by Tole atmospheric drought index (19 vs. 18), and the frequency of "light drought" events in the former is lower with respect to the latter (11 vs. 12). This means that the Shule runoff is more stable than the rainfall in the Shule river drainage area. However, it is not the case when taking station Qilian (Menyuan) relative to the Hei (Shiyang) basin into account (see Tables 5 and 7 for the related frequencies). This is because the runoff volume for the inland rivers depends on not only upstream precipitation but also atmospheric temperature as a determinant for melting water from glaciers. According to research by Xu, 1997, about 28.5%, 8.3% and 3.8% of the runoff volume come from the melted glaciers in the Shule, Hei and Shiyang River, thereby the Shule runoff has its water volume of glacier origin far greater compared to the two other rivers. Therefore, even in the year with less rainfall but higher temperature in the upstream mountains, the Shule can still maintain its usual runoff. Take the case in 1961 as an example, although the atmospheric drought index at Tole is indicated a "drought" grade, but a "normal" grade is given into runoff-index of the Shule River. Again, from mean temperature anomalies across April–June annually in 1959–2004 (figure not shown), there is positive temperature anomaly in 1961, a situation is favorable for melting glaciers and the same is true for 1978, 1991, 1995 to 1998 and 2001. Therefore, the runoff-denoted drought index Z (Z_{rd} hereafter) should consider both temperature and rainfall in upstream mountains.

Table 7 – Flood/drought categories resulting from the combination done for Table 5.*.

Category	D/F	Events			MFD
		Tole	Qilian	Menyuan	
1	Flood	3	2	2	5.3%
2	Light flood	10	12	12	23.9%
3	Normal	18	19	17	40.9%
4	Light drought	12	12	13	27.3%
5	Drought	3	1	2	4.6%

* D/F = drought or flood, and MFD = mean frequency distribution.

3.4. Relationship between Z_{rd} grades and irrigation

Agriculture in the arid climate of Hexi Corridor completely depends on the irrigation. When runoff is high, irrigation is possible and vice versa. For low-level runoff, underground water has to be extracted for supplement. Considering the fact that water resources such as the underground water are the vital condition to guarantee sustainable development on an agricultural basis, the runoff from inland rivers should be used as much as possible. With their water originating from snow/ice melting and precipitation over the Qilian Mountains, we have good chance to minimize or entirely cease the tapping of underground water.

Based on the above discussion, a scheme of 5 Z_{rd} grades is constructed for representing the flow volume of these inland rivers. In practice, as soon as runoff reaches the categories 1, 2 and 3, meaning that the runoff is "higher-level" or "normal", irrigation is likely needed. Since irrigation is a human activity, "plentiful" water shown by runoff level does not mean waterlogging on farmland and can be used in an efficient way instead. For this reason, runoff-given "flood", "light flood" and "normal" grades are put into one grade as "normal".

When runoff-denoted grades are the 4th ("light drought") and 5th ("drought"), runoff is hard enough to satisfy the needs of irrigation. Drought denoted lower runoff implies that the runoff from inland rivers can not supply enough water for agricultural purposes. In that case, irrigation has to be depended on underground water. Referring to Table 5, it can be seen clearly that the "drought" grade emerges at a frequency of as low as 4.3%, suggesting that low-frequency underground water exploitation is feasible enough to keep agricultural sustainable development going. In case of runoff-denoted "light drought" as a signal of insufficient water flowing through the inland rivers for irrigational purposes, its severity in Table 5 is re-separated in the following way: The middle value −1.0846 of Z_{rd} between −0.5244 and −1.6448 is taken for use. With $-1.0846 < Z < -0.5244$ set, Z_{rd} denotes a "slightly light drought" event, indicating that a science plan should be scheduled for runoff utilization. It is suggested to delay the time for first operation of introducing river water in an effort to guarantee the irrigation at a crucial time for wheat growth, next being the discharge of water from a reservoir to replenish the low-level runoff, and with $-1.6448 \leq Z \leq -1.0846$ set, heavy drought is likely to occur, thus leading to the necessity of properly extracting underground water in addition to the suggested countermeasures.

In summary, Z values are separated into 4 grades as indicators of irrigations (Table 8).

3.5. Relationship between runoff drought index and spring wheat yield

3.5.1. The qualitative relationship

On a theoretical basis, the presented Z_{rd} in this work can be employed to determine drought severity harmful to agriculture. With the discussion in the evolvement of Z_{rd} and climate yield of Hexi corridor spring wheat, the relationships between Z_{rd} and the yields are obtained during 1959–2004.

Table 8 illustrates the runoff-denoted drought indices Z_{rd} values related to irrigation of different drought categories of Z (denoted as Z_{ir}). Obviously, the larger (absolute value) the Z_{ir}, the more severe the dryness would be. Fig. 3 shows the association between Z_{ir} from three typical stations on the respective rivers with the climate yield of spring wheat in the related irrigation zones. Overall, the figure indicates that Z_{ir} values vary with the climate yield over each basin in an opposite manner. Namely, the larger is the Z_{ir} (absolute value), the lower the climate yield in 1959–2004.

3.5.2. A multiple regression yield equation

Two steps are adopted in order to construct a multivariate equation which takes into account the influence of Z_{ir} to estimate spring wheat yield in Hexi irrigation area. Firstly, considering the possible factors that influence the wheat yield, we selected temperature, precipitation and runoff from January to June in the same year and July to December in previous year as the backup factors (total 36 factors) to establish a multiple regression yield equation. With the use of the stepwise regression method (Draper and Smith, 1981) and the stepwise elimination scheme to remove those factors whose influence are insignificant to yield, an optimization regression equation is obtained. Secondly, taking Z_{ir} and spring wheat yield derived from the above optimization regression equation as two factors to establish a multi-variate equation again. The second regression equation has been improved with either multiple correlation coefficient (R) or the F-test value (F).

Following the above procedure, the expressions of yield regression equation at three irrigation stations are as follows.

At Jiuquan station, considering temperature, precipitation and runoff in every month, uses the stepwise elimination scheme to construct the regression equation, a climatic yield forecast equation can be obtained:

Table 8 – Z_{rd} values related to irrigation of different drought categories, to distinguish the grades represented by the runoff-denoted drought indices Z_{rd} (see Table 4) from the 4 grades irrigation associated categories of Z in this Table.

Category	Z value	Related drought severity and irrigation
1	$Z \geqq -0.5244$	For "normal", and no operation needed
2	$-1.0846 < Z < -0.5244$	For "slightly light drought", and delaying the time of first irrigation, use of reservoir water
3	$-1.6448 \leq Z \leq -1.0846$	For "heavier drought", and delaying the time of first irrigation, use of reservoir water and appropriate extraction of underground water
4	$Z < -1.6448$	For "drought", and necessity of utilizing underground water

Z of this Table is denoted as Z_{ir} to indicate the levels of normal, light drought, heavier dryness and real drought for categories 1–4, respectively.

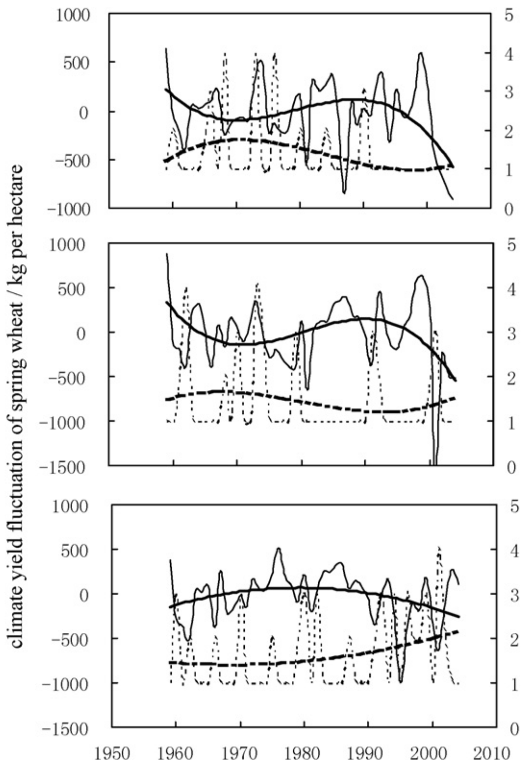

Fig. 3 – Z_{ir} (dashed) in association to the climate yield of spring wheat (solid line) at the irrigation zones of Jiuquan of the Shule basin (a), Zhangye of the Hei valley (b) and Wuwei of the Shiyang reach (c), thick dashed and solid lines denote 3-order trend curve of Z_{ir} and climate yield, respectively.

$$Y_{yield01} = 656.3 - 40.6x_{p1} + 17.4x_{p3} - 13.7x_{p6} + 4.1x_{p8} + 2184.8x_{r1} - 4682.1x_{r3} - 1227.4x_{r4} + 2511.7x_{r12} \quad (13)$$

where $Y_{yield01}$ denotes climatic yield influenced by precipitation and runoff. x_{p1}, xp_3, x_{p6} and x_{p8} represent the monthly precipitation in January, March, June and August, respectively. x_{r1}, x_{r3}, x_{r4} and x_{r12} denote the monthly runoff in January, March, April and December, respectively. As the validation results, the multiple correlation coefficient (R) is 0.74, and the F-test value (F) is 9.0.

It is apparent in the equation (Eq. (13)) that the products of spring wheat in Shule irrigating area are negatively related to the precipitation in January and June and the runoff in March and April. Although this fact may be opposite from the common sense, as already mentioned in Section 3.3, the runoff in Shule irrigating area is mainly come from snow and ice melting instead of the precipitation. According to a recent study, the temperature at the representative station (i.e., Jiuquan Station) in Shule irrigating area is negatively correlated with the precipitation in the area. Specifically, the monthly mean temperature in Jiuquan is −8.9 °C in the month of January. It is a relatively low temperature. If there were more precipitation in the area, the temperature would be even lower. As the consequence, the depth of frozen soil will be deeper. The warm-up period in spring will be later than usual. These conditions, however, have negative impacts on the seeding as they can cause the miss of proper time of the seeding. As a result, the product will decrease. In contrast, month of June is a milking stage of the spring wheat. Compared with sunshine condition, more precipitation has negative impact on the maturity of the wheat during this period. It usually causes the decrease of the product.

In the Shule River area, rainfall amount is usually small during March and April. Runoffs mainly come from the snow and ice melting but not from the precipitation. In addition, the precipitation type is commonly the snow in March and April. Therefore, more precipitation implies lower temperature and less snow melting and runoff in the area. Thus, the runoff is negatively related to the precipitation rate in March and April. On the other hand, the precipitation in the irrigating area is positively related to product of spring wheat. This means that more runoffs correspond to higher temperature and less precipitation. As the results, the product decreases.

Next, considering the Z_{ir} in the key period of crop growth, another improved climatic yield forecast equation can be obtained:

$$Y_{yield} = 60.7 - 40.0Z_{ir} + 1.0Y_{yield01} \quad (14)$$

where Y_{yield} denotes the climatic yield influenced by synthesis factors. The multiple correlation coefficient (R) improves as 0.78, and the F-test value (F) improves as 31.9. At the same time, the root mean square error (RMSE) between observed and simulated spring wheat yield is 209.9 kg ha^{-1}.

Z_{ir} is a variable that mainly reflect the degree of the drought in the key growth period of spring wheat. It should note that, in the first step of the regressive equation (Eq. (13)), Z_{ir} was ignored. But, Z_{ir} has been considered in the second step when adjust the forecasted spring wheat production in Eq. (14). The purpose of composited Eq. (14) is to produce a better prediction of the wheat products. Overall, with composition of two kinds of the equations (Eqs. (13) and (14)), the forecasted production of spring wheat is much improved. Therefore, it is anticipated that the forecast equations created in this study are useful in operational.

Repeating above steps at Zhangye, we get the following results:

$$Y_{yield01} = -21.2 - 5.4x_{p7} + 247.1x_{r6} - 113.1x_{r7} + 102.0x_{r8} + 85.7x_{r9} - 2032.4x_{r11} \quad (15)$$

where $Y_{yield01}$ denotes climatic yield influenced by precipitation and runoff. x_{p7} denotes the monthly precipitation in July. x_{r6}, x_{r7}, x_{r8}, x_{r9} and x_{r11} denote the monthly runoff in June, July, August, September and November, respectively. The R is 0.69, and the F is 7.2 in the case.

Eq. (15) implies that the product of spring wheat has a negative relationship with precipitation in July and runoffs in July and November. The runoff and precipitation are synchronization in July owing to the former lies on the later. In July, the wheat is grown up and does not need more precipitation. There is very little rainfall in November in Hei river area. The high runoffs indicate a warm weather, which leads more ice and snow melting, and more evaporation at the same time. More evaporation reduces the water content or soil moisture, thus negatively impact on the seeding of the spring wheat next year. In other words, high runoffs in November lead a high temperature and more evaporation, then low product of spring wheat.

Following the reasons to derive Eq. (14), another improved climatic yield forecast equation can be obtained:

$$Y_{yield} = 111.9 - 74.7Z_{ir} + 0.9Y_{yield01} \quad (16)$$

where Y_{yield} denotes the climatic yield influenced by synthesis factors. The R improves as 0.71, and the F improves as 21.2. At the same time, the root mean square error (RMSE) between observed and simulated spring wheat yield is 219.6 kg ha^{-1}.

At the Wuwei Station:

$$Y_{yield01} = -700.2 - 34.2x_{p2} + 6.1x_{p5} - 4818.1x_{r3} + 531.9x_{r4} + 318.8x_{r5} + 1000.4x_{r6} + 2185.8x_{r11} \quad (17)$$

where $Y_{yield01}$ denotes the climatic yield influenced by precipitation and runoff. x_{p2} and x_{p5} denote the monthly precipitation in February and May, respectively. x_{r3}, x_{r4}, x_{r5}, x_{r6} and x_{r11} represent the monthly runoff in March, April, May, June and November, respectively. The R is 0.67, and the F is 7.6 in Eq. (17).

In Eq. (17), the products of spring wheat have negative relationship with the precipitation in February and runoff in March. Statistic indicates that the temperature at Wuwei station, a representative station in the area, have negative relationship with the rainfall. In other words, more precipitation will accompany with a low temperature in February that leads to deeper soil frozen. As the result, the later seeding in the next spring will cause the reduction in the product of spring wheat. Similar explanation can be applied to explain why the runoffs in March have a negative relationship with the product of spring wheat in Eq. (13).

Similar to Eq. (14), the improved climatic yield forecast equation can be obtained as follows when Z_{ir} is considered:

$$Y_{yield} = 51.5 - 35.3Z_{ir} + 0.9Y_{yield01} \quad (18)$$

where Y_{yield} denotes the climatic yield influenced by synthesis factors. With this equation, the R became 0.69, and the F changed to 19.1. At the same time, the root mean square error (RMSE) between observed and simulated spring wheat yield is 203.5 kg ha^{-1}.

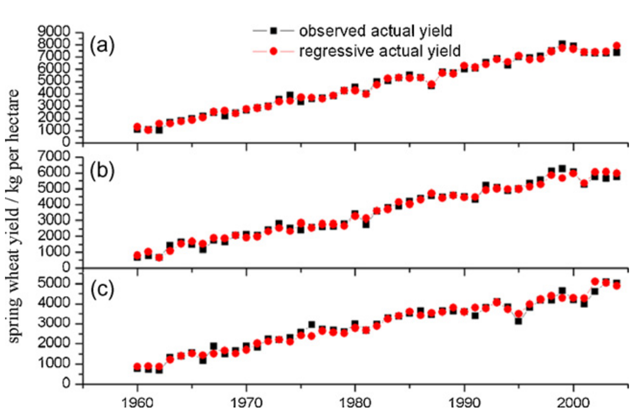

Fig. 4 – The comparison curves between the observed and the regressive actual yield of crop at three agro-meteorological stations Jiuquan of the Shule basin (a), Zhangye of the Hei valley (b) and Wuwei of the Shiyang reach (c).

Consequently, the regressive spring wheat climate yield will be obtained based on the above Eqs. (14), (16) and (18) at three agro-meteorological stations, respectively. Then, the regressive actual yield of a crop will be obtained by the Eq. (10) mentioned above.

Fig. 4 shows the observed actual yield of a crop and those estimated by the regression equations at three agro-meteorological stations. Evidently, the simulation effects at Jiuquan and Zhangye is better than those at Wuwei. Overall, differences between observed yield and simulated value are rather low in three stations. This means that the regressive equation can be utilized to predict the wheat yield.

4. Conclusions and discussion

The inland river runoffs in Hexi region obey the Pearson type III distribution in the study period. The probability density function of the runoff can be translated into a standard normal distribution with Z as the variable in normalizing process. Then, a drought index denoted by runoff (Z_{rd}) is obtained, and its grades are confirmed corresponding to its theoretic frequencies of the standard normal distribution. Based on this investigation, the analysis of irrigation volumes, Z_{rd} is divided into 4 grades and renamed as Z_{ir} in accordance with irrigation in the cropping zones, followed by rational suggestions proposed for the planned use of water. On the other hand, the definition of Z_{ir} lays a theoretical foundation for planned irrigation. Z_{ir} varies with the trends of spring wheat climate yields in an opposite manner. According to the relationships between the yield of spring wheat yield and Z_{ir}, the trend of yields can be qualitative predicted. By using the stepwise regression method and the stepwise elimination scheme, a multi-variate regression equation is obtained to calculate spring wheat yield with considering Z_{ir} in the Hexi irrigation areas. Through the regressive equation, the quantitative prediction of wheat yield can be achieved.

To summarize, the runoff-denoted drought index is useful for Hexi corridor, where agriculture depended on water from inland rivers rather than precipitation. The grades of runoff-denoted drought index can be applied for planning the water usage of irrigation and predicting the trend of spring wheat yield in the irrigated zones. The drought criterion in the irrigation zone, Z_{ir}, plays a guiding role in the trend prediction. It can be very useful in the practice.

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