TYPE Original Research
PUBLISHED 23 June 2023
DOI 10.3389/fenvs.2023.1210256

OPEN ACCESS

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RECEIVED 22 April 2023
ACCEPTED 15 June 2023
PUBLISHED 23 June 2023

CITATION
Duan J, Zhao J, Sun G and Gao F (2023), Spatio-temporal variation of water requirement and meteorological impact factors of maize Shaanxi, China.
Front. Environ. Sci. 11:1210256.
doi: 10.3389/fenvs.2023.1210256

Spatio-temporal variation of water requirement and meteorological impact factors of maize Shaanxi, China

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To quantitatively reveal the characteristics of the spatial and temporal distribution and the influencing factors of the maize water requirement in Shaanxi Province, the Penman-Monteith model and path analysis were used to systematically analyze the interannual variation and spatial distribution of the maize water requirement at different growth stages in three climatic zones in Shaanxi Province. And the relationship between the water requirement and meteorological factors based on daily meteorological data in Shaanxi Province for the past 60 years. The results showed that the maize water requirement during the whole growth period decreased from 1960 to 1989, with a rate of change of –2.08 mm/a, increased from 1989 to 2019, with a rate of change of 0.38 mm/a, and decreased from 1960 to 2019, with a rate of change of –0.46 mm/a. The water requirement of maize decreases from north to south during the whole reproductive period. That of seedling and male stage are more in the Guanzhong, followed by the north and the least in the south. The water requirement of maize at jointing stage increased from north to south. And the water requirement distribution is more in the north, followed by the south and the least in the Guanzhong area during the maturity period. The average temperature and the duration of the sunshine are the key factors that affect maize water requirement in Shaanxi Province, and have an increasing effect on water requirement, wind speed has an increasing effect on water requirement but is not obvious, water vapor pressure and relative humidity have an inhibiting effect on water requirement. For spring maize, the promoting effect of the duration of the sunshine on maize water requirement was gradually strengthened from north to south. The promoting effect of mean temperature and wind speed decreased gradually. The inhibitory effect of water vapor pressure and relative humidity decreases continuously. This study can provide a scientific basis for the management of irrigation quota in maize growing areas under similar cropping conditions.

KEYWORDS

sustainable agricultural development, crop water demand, spatial and temporal distribution characteristics, meteorological factors, path analysis

1 Introduction

China is a large agricultural country. In 2021, the total planted area of food crops in China accounted for about 70% of the total planted area of crops in the country, of which the planted area of rice, wheat and maize accounted for 83% of the total planted area of food crops (China Statistical Yearbook, 2022). Meanwhile, China is also a country with scarce water resources, and agricultural water, being the largest industrial water use, accounts for 61% of the total water resources used in the country (China water resources bulletin, 2022). Shaanxi Province is located in the northwest of China where water resources are scarce, and is one of the most water-stressed provinces in the country. The distribution of water resources in the province is seriously uneven, with the southern region, which accounts for 36% of the province's land area, having more than 70% of the province's water resources, while the northern and central regions have serious water shortages and largely affect the region's food production (Ren et al., 2017). In order to promote sustainable and healthy development of agriculture, there is an urgent need for spatial allocation of water resources. Understanding the laws of agricultural water use can, on the one hand, save water resources and alleviate the contradiction between water supply and water use in Shaanxi Province, and on the other hand, explore the relationship between maize water requirement and yield to achieve optimal yield and increase economic benefits.

To alleviate the problem of water stress, water-saving irrigation needs to be developed, and water-saving irrigation urgently needs to clarify the water requirements and growth characteristics of crops. Maize as the third crop in China's main grain cultivation area, the average multi-year water requirement in 285–987 mm/year, with significant differences in water requirement in different regions (Shang et al., 2022). From the national spatial distribution, the water requirement of maize in the northwest is higher than that in the southeast. From the time series analysis, due to the large area of China and the obvious differences between different regions, the trend of maize water requirement over time varies among provinces and needs to be further studied by province and region. Many scholars have analyzed the spatial and temporal distribution characteristics of maize water requirement at the national, watershed and provincial scales, but studies involving maize water requirement in Shaanxi Province are lacking, and they are mainly concentrated in Guanzhong area. Liu et al. (2009) studied the national crop water requirement and analyzed in the Jin-Shaan-Gan region and obtained the conclusion that the water demand of spring maize crop is between 450 and 750 mm while that of summer maize is between 250 and 450 mm. The study area is too broad and the range of water requirements is too large to guide agricultural production. Wang and Niu (2014) studied the summer maize water demand in the Guanzhong irrigation area and obtained values between 400 and 500. Their study area was only the Guanzhong area and spatial and temporal characteristics were not analyzed. At present, there is a lack of research on the spatial and temporal distribution of maize water requirement at the provincial scale in Shaanxi Province. Supplementing this part of research can save water resources for agriculture and alleviate the contradiction of water supply in Shaanxi Province.

Under the background of climate warming, the interaction between meteorological factors changes simultaneously, which changes the spatial-temporal pattern of soil moisture and climate productivity, thus affecting maize growth and agricultural water use (Kuwagata et al., 2018; Jinger et al., 2022). Research on the spatial and temporal variation of maize growth water requirement under climate change has become an important measure to ensure food production, reduce irrigation water input and improve water use efficiency (Babu et al., 2015; Soleymani and Shahrajabian, 2017; Liu et al., 2021). Meteorological factor is an important factor affecting crop water requirement. In order to explore the influence degree of various meteorological factors on crop water requirement under climate change and promote the sustainable development of agriculture, many scholars have conducted a lot of studies on the relationship between temporal and spatial evolution of crop water requirement and meteorological factors (Cao et al., 2008; Xing et al., 2022; Wu and Yang, 2023). The relationship between crop water requirements and meteorological factors can be investigated from two perspectives: full fertility and sub-fertility stages, each of which has its own growth and management requirements (Muneer et al., 2018; Mthembu et al., 2022), and different fertility stages have different sensitivity to meteorological factors (Luo and Batur, 2017; Xue et al., 2018).

As a typical region with severe water scarcity, Shaanxi Province has a large amount of irrigation water and obvious spatial variability in water distribution. Meanwhile, the natural environment is obviously different, from north to south across the three monsoon climate zones of temperate, warm temperate and northern subtropical. As maize is the main crop grown in Shaanxi Province, this study subdivides Shaanxi Province into three study areas based on climatic and geographical conditions, and divides the time series into two time periods according to the magnitude of changes to study in depth the characteristics of spatial and temporal changes in maize water requirement at different fertility stages and meteorological factor attribution analysis. This study could supplement the lack of research on maize water requirement in Shaanxi Province and provide scientific support for crop agricultural water management in the maize growing region of Shaanxi Province.

2 Methods

2.1 Data source

Based on the principle that the data time series are as long as possible and as many stations are selected as possible, and due to the different years of meteorological stations in Shaanxi Province, this paper selects day-by-day meteorological data from 34 stations in Shaanxi Province from 1960 to 2019. The data set includes rainfall, sunshine, average temperature, maximum temperature, minimum temperature, wind speed, relative humidity, etc. The meteorological data were obtained from the China Meteorological Data Network.

2.2 Study area

Shaanxi Province straddles three climatic zones, from north to south, the temperate zone, the warm temperate zone and the northern subtropical zone, with marked climatic differences within its borders. The distribution of annual precipitation decreases from south to north and is significantly influenced by

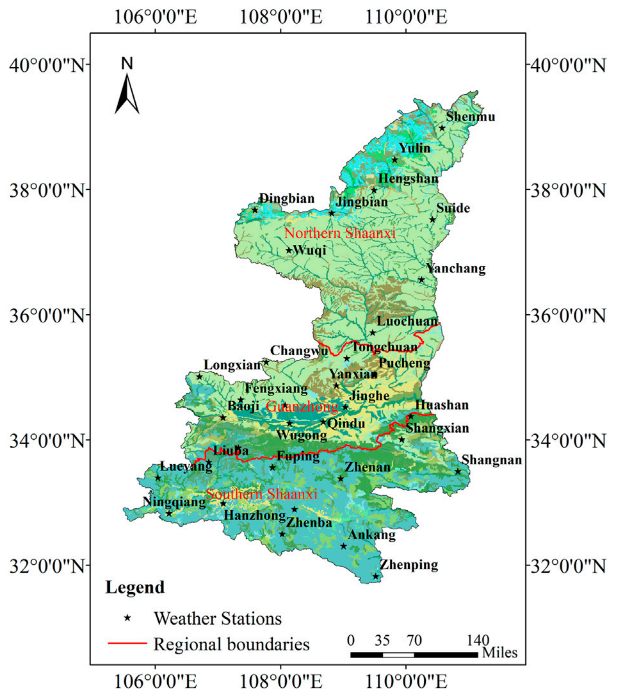

FIGURE 1
Study area and distribution of stations.

the mountainous terrain. The spatio-temporal distribution of water resource in Shaanxi Province is uneven, which is one of the most water-stressed provinces. The terrain of Shaanxi Province is generally high in the north and south, low in the middle, with the northern mountains and the Qinling Mountains dividing Shaanxi into three natural regions: the northern Shaanxi Plateau in the north, the Guanzhong Plain in the center and the Qinba Mountains in the south.

The main grain crops in Shaanxi Province are wheat, rice, maize and soybeans, etc. The maize growing area is spread all over the province, and maize accounts for 24.30% of the area sown with grain crops. In 2019, Shaanxi's maize output reached 6,095,800 tons, accounting for 49.51% of the total. Among them, maize production in the Guanzhong region accounted for 55.18% of the province's maize production. Soil fertility has a direct impact on land productivity. The chestnut soil and black soil in northern Shaanxi, the podzolic soil and primitive soil in mountainous areas in southern Shaanxi, and the aeolian sand and saline-alkali soil in various regions generally have poor fertility and low production level, while the distribution areas of the oil soil in Guanzhong Basin and paddy soil in Hanjiang Valley are relatively high yielding areas. In this paper, Shaanxi Province is divided into three regions based on geographical location and climatic differences, including northern Shaanxi, Guanzhong and southern Shaanxi. Based on the combination of climatic environment and topographic features, northern Shaanxi and southern Shaanxi are suitable for annual spring maize, while Guanzhong is suitable for growing summer maize. The distribution map of the study area and meteorological stations is shown in Figure 1.

2.3 Crop water requirement

The crop water requirement refers to the amount of water consumed by maize during the growth season, which is relatively stable in specific crop yield conditions and areas. Water requirement of maize is mainly calculated through field experiments, and can also be calculated by theoretical methods. In this paper, the crop coefficient method recommended by FAO is adopted for calculation, and the formula is shown in the following equation (Allen et al., 1998):

$$\mathrm{ET_c} = K_c \cdot \mathrm{ET_0} \tag{1}$$

Where $\mathrm{ET_c}$ is the crop water requirement, mm; K_c is the crop coefficient; and $\mathrm{ET_0}$ is the reference crop evapotranspiration, mm.

The reference crop evapotranspiration is calculated by the Penman-Monteith method recommended by FAO56 as follows (Allen et al., 1998),

$$\mathrm{ET_0} = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.342U_2)} \tag{2}$$

Where Δ is the slope of saturated water vapor pressure-air temperature curve, kPa/°C; R_n is the net radiation on crop surface, MJ/(m2·d); G is the soil heat flux, MJ/(m2·d); γ is the psychrometric constant, kPa/°C; T is the mean daily air temperature,°C; U_2 is the wind speed at 2 m height above the ground, m/s; e_s is the saturated water vapor pressure, kPa; and e_a is the actual water vapor pressure, kPa.

In this paper, maize fertility is divided into four stages according to the characteristics of maize growth: seedling stage, jointing stage, male stage and maturity stage. The time points of each fertility stage are based on experiments and studies conducted by other scholars (Liang et al., 2011; Li et al., 2015; Qin et al., 2016; Cheng et al., 2018) and are shown in Table 1. The Guanzhong Plain is suitable for growing summer maize due to the advantages of soil and climate, so its planting time is quite different from other areas.

Crop coefficients: The piecewise single value average method recommended by FAO-56 in 1998 was adopted to calculate the crop coefficient, which should be revised according to the actual local situation when used. The value of the modified maize coefficient was referred to the studies of Liang (2011), Kang (1990), Liu (2009), Lu et al. (2019), and the revised values of crop coefficients are shown in Table 2.

2.4 Path analysis

All meteorological factors can directly or indirectly affect crop water requirement with different degrees of influence. In order to analyze the direct or indirect effect of each meteorological factor on crop water requirements, this paper uses the path analysis method. When n independent variables and one dependent variable y interact with each other, the following regression equation can be established:

$$y = b_0 + b_1 x_1 + b_2 x_2 + \cdots + b_n x_n \tag{3}$$

where b_n is an unstandardized coefficient.

TABLE 1 Development stages of spring and summer maize.

Partition	Seedling stage	Jointing stage	Male stage	Maturity
Northern Shaanxi (spring maize)	the last 10-day period of April	middle of June	the first 10 days of July	the last 10-day period of August
Guanzhong (summer maize)	middle of June	the first 10 days of August	the first 10 days of September	the last 10-day period of September
Southern Shaanxi (spring maize)	the first 10 days of April	middle of July	the last 10-day period of July	the last 10-day period of August

TABLE 2 Revised maize coefficients at different growth stages.

Partition	Seedling stage	Jointing stage	Male stage	Maturity
Northern Shaanxi (spring maize)	0.56	0.73	1.16	0.9
Guanzhong (summer maize)	0.61	0.93	1.27	1.07
Southern Shaanxi (spring maize)	0.55	0.8	1.18	1.18

The above equation can be mathematically converted into a regular matrix equation:

$$\begin{bmatrix} 1 & \gamma_{x_1x_2} & \cdots & \gamma_{x_1x_n} \\ \gamma_{x_2x_1} & 1 & \cdots & \gamma_{x_2x_n} \\ \vdots & \vdots & \vdots & \vdots \\ \gamma_{x_nx_1} & \gamma_{x_nx_2} & \cdots & 1 \end{bmatrix} \begin{bmatrix} P_{x_1y} \\ P_{x_2y} \\ \vdots \\ P_{x_ny} \end{bmatrix} = \begin{bmatrix} \gamma_{x_1y} \\ \gamma_{x_2y} \\ \vdots \\ \gamma_{x_ny} \end{bmatrix} \quad (4)$$

where, $\gamma_{x_ix_j}$ $(i = 1, 2, \ldots, n; j = 1, 2, \ldots, n)$ is the correlation coefficient of x_i and x_j; P_{x_iy} $(i = 1, 2, \ldots, n)$ is the direct pass-through coefficient, which is the direct effect of the independent variable x_i on the dependent variable y, the greater the absolute value of the coefficient, the stronger the direct effect; γ_{x_iy} is the total indirect effect of the independent variable x_i on the dependent variable y through the other independent variables, $\gamma_{x_ix_j}P_{x_iy}$ is the indirect pass-through coefficient, which is the indirect effect of the independent variable x_i on the dependent variable y through the independent variable x_j, the greater the absolute value of the coefficient, the stronger the indirect effect.

The decision coefficients is:

$$R_i^2 = b_i^2 + 2\sum_{j\neq i} b_i\gamma_{ij}b_j \quad (5)$$

where R_i^2 is the decision coefficient, which reflects the combined determining role of x_i on y, including the direct and indirect determining role of x_i on y. If R_i^2 >0, it indicates that x_i plays an enhancing role on y. If R_i^2 <0, it indicates that x_i plays a limiting role on y. The greater the absolute value of the decision coefficient, the stronger the comprehensive determining effect of x_i on y.

2.5 Data processing

The meteorological data were rigorously checked and corrected, and ETo Calculator was used to calculate the potential evapotranspiration of the crop. The P-M formula and the single-crop coefficient method were used to calculate the maize water requirement at 34 meteorological stations. The spatial distribution map of maize water requirement was mapped by the inverse distance weight interpolation method of Arcgis software. The relationship between meteorological factors and maize water requirement was studied by using correlation analysis and path analysis.

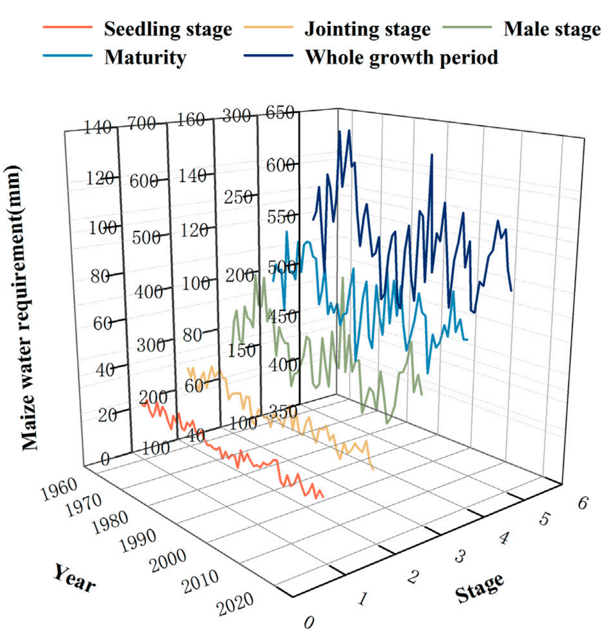

FIGURE 2
Variation process of maize water requirement during growth period in Shaanxi Province.

TABLE 3 Variation trend of water requirement of maize at different growth stages.

	Seedling stage	Jointing stage	Male stage	Maturity	Whole growth period
First period	−0.11 mm/a	−1.00 mm/a	−0.33 mm/a	−0.78 mm/a	−2.23 mm/a
Second period	0.11 mm/a	0.10 mm/a	0.07 mm/a	0.12 mm/a	0.41 mm/a
Full period	−0.01 mm/a	−0.20 mm/a	−0.08 mm/a	−0.21 mm/a	−0.59 mm/a

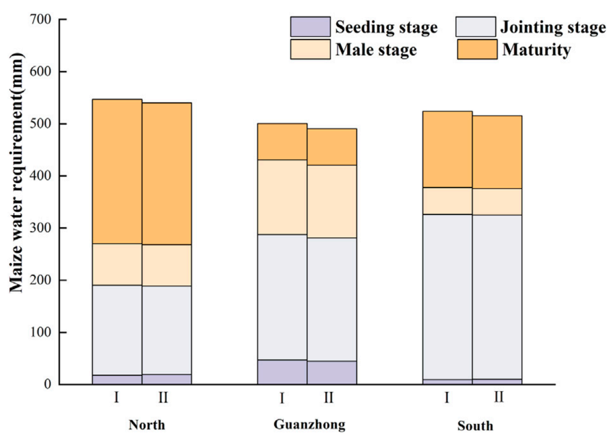

FIGURE 3
I (1960–1989) and II (1989–2019) variation in water requirements of maize at different time stages of each growth stage.

3 Results

3.1 Spatial and temporal trends in water requirement of maize

3.1.1 Temporal characteristics

In Shaanxi Province, the water requirement of maize during the whole reproductive period 1960–2019 showed a decreasing trend with a rate of change of −0.59 mm/a. The maximum value of water requirement was 598.17 mm in 1972, and the minimum value was 453.73 mm in 1989. The trend and rate of change of water requirement of maize in different reproductive periods were different, and all reproductive stages showed a decreasing trend on the whole (Shown in Figure 2). The decreasing trend of water requirement of maize at the jointing stage was the most obvious, with a rate of change of −0.20 mm/a, followed by a rate of change of −0.16 mm/a at the maturity. Then it shows a slightly decreasing trend of −0.09 mm/a at the male stage, and an almost negligible trend of −0.01 mm/a at the seedling stage.

From Figure 2, it can be seen that the overall water requirement of maize showed a decreasing trend, with an abrupt change in 1989 and a significant difference in the amplitude before and after 1989, with a decreasing trend of −2.09 mm/a from 1960 to 1989 (first period) and an increasing trend of 0.38 mm/a from 1989 to 2019 (second period). The different growth periods of maize also showed different trends in the first and second periods. The water requirement of maize at the seedling stage showed a decreasing trend with a rate of change of −0.11 mm/a in the first period and an increasing trend with a rate of change of 0.11 mm/a in the second period. The water requirement of maize at the jointing stage showed a decreasing trend with a rate of change of −1.00 mm/a in the first period and an increasing trend with a rate of change of 0.10 mm/a in the second period. The water requirement of maize at the male stage showed a decreasing trend with a rate of change of −0.36 mm/a in the first period and the rate of change in the second period was 0.08 mm/a. The rate of change of maize water requirement in the maturity period was −0.62 mm/a and in the second period was 0.10 mm/a (Shown in Table.3). By comparing the change trend of maize water requirement at two time stages, it can be concluded that the change rate of maize water requirement at jointing stage and maturity stage increases most obviously.

As can be seen from Figure 3, the proportion of water requirement of maize at each fertility stage was different in different regions. Shaanxi Province from north to south transition into temperate zone, warm temperate zone and north subtropical zone, and the climate difference is obvious. Spring maize is planted in the north, which is in the temperate zone and the maturity period accounts for a large proportion. Summer maize is planted in Guanzhong area, which is in the warm temperate zone, and the jointing period accounts for a large proportion. Spring maize is planted in the south of Shaanxi province, which is located in the north subtropical zone. The water requirements of different growth stages in the first stage in northern Shaanxi are 17.65 mm, 172.58 mm, 79.81 mm and 276.78 mm, accounting for 3.23%, 31.56%, 14.60% and 50.62% respectively. The proportion of water requirement in seedling stage and male stage in the second period increased by 0.30% and 0.11% compared with that in the first period, respectively. The proportion of jointing stage and mature stage decreased by 0.12% and 0.29% compared with the first stage. In Guanzhong area, the water requirements at different growth stages in the first stage were 46.84 mm, 240.94 mm, 143.01 mm and 69.54 mm, accounting for 9.36%, 48.46%, 28.58% and 13.90%, respectively. Compared with the first period, the proportion of water requirement in jointing period and maturity period increased by 0.03% and 0.37% respectively. The proportion of seedling stage and tasseling stage decreased by 0.24% and 0.15% compared with the first stage, respectively. The water requirements of different growth stages in the first stage in southern Shaanxi were.9.51 mm, 316.57 mm, 51.73 mm and 146.10 mm, accounting for 1.82%, 60.42%, 9.87% and 27.89%, respectively. The proportion of water requirement at seedling stage, jointing stage and tasseling stage in the second period increased by 0.08%, 0.72% and 0.01%, respectively, compared with the first period. The proportion of mature period decreased by 0.80% compared with the first period.

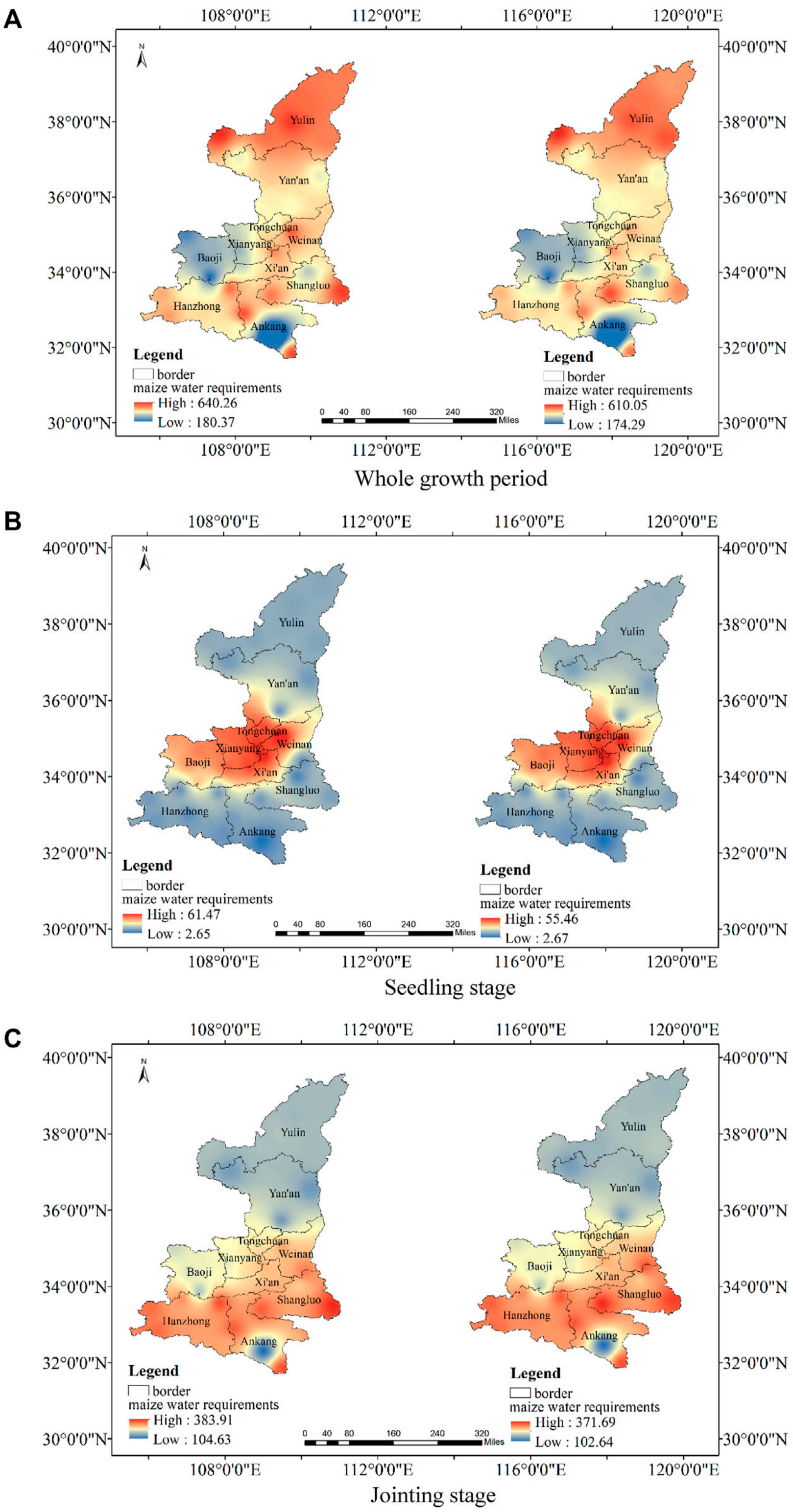

FIGURE 4
Spatial dynamic process of water requirement of maize. **(A)** Whole growth period. **(B)** Seedling stage. **(C)** Jointing stage. **(D)** Male stage. **(E)** Maturity.

3.1.2 Spatial characteristics

The spatial distribution of maize water requirement during the whole reproductive period and each reproductive stage is shown in Figure 4, which shows an overall decreasing trend from north to south during the whole reproductive period of maize in Shaanxi Province, with a range of 180.37–640.26 mm for the first period and

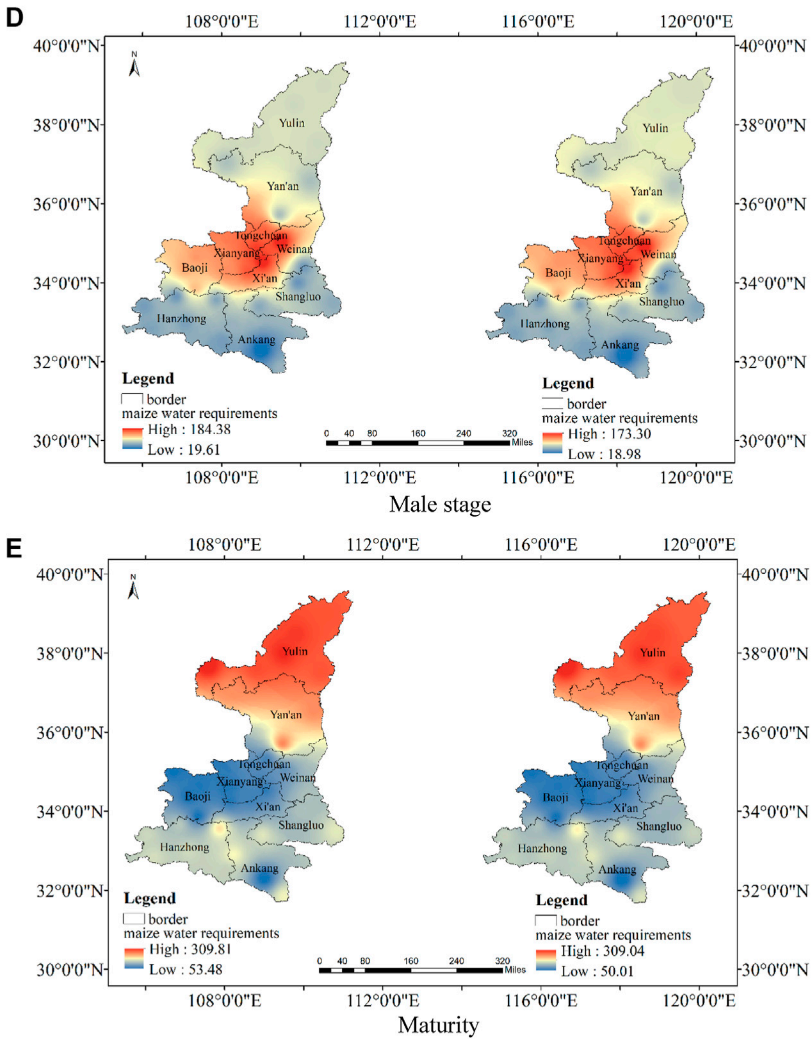

FIGURE 4

174.29–610.05 mm for the second period (Shown in Figure 4A). The spatial distribution of the average annual water requirement of maize in the two periods remained basically unchanged.

The distribution of maize water requirement at different fertility stages is obviously different, shown in Figures 4B–E. The water requirement at the seedling stage and the male stage is more in the central part of the province, followed by the northern part and the least in the southern part. Maize water requirement at jointing stage increased from north to south, and reached the minimum in the central and southern part of Ankang City in southern Shaanxi Province. The distribution of water requirement at maturity stage is higher in the north, second in the south and least in the Guanzhong area. The spatio-temporal distribution in the first period and the second period is basically the same, but the range of high and low values is slightly reduced, indicating that the water requirement of maize in Shaanxi Province presents the same range of change in the whole province.

The multi-year average water requirement of maize was greater in the first time period than in the second time period, decreasing by 10.08 mm in the whole reproductive period and by 0.31 mm, 3.59 mm, 2.06 mm, and 4.00 mm in the seedling, jointing, male, and maturity stages, respectively. The spatial distribution of maize water requirement at different periods was basically the same, but the high and low values were slightly different.

3.2 Analysis of factors influencing maize water requirement

3.2.1 Correlation analysis

There are many meteorological factors affecting crop water requirement. In this paper, sunshine duration, average temperature, wind speed, average water vapor pressure and relative humidity are selected as the key factors affecting maize water requirement. Through the correlation analysis of each meteorological factor and maize water requirement, we obtained that the water requirement of maize in Shaanxi Province was positively correlated with sunshine, average temperature and wind speed, with correlation coefficients of 0.852, 0.395 and 0.646, respectively; and negatively correlated with average water

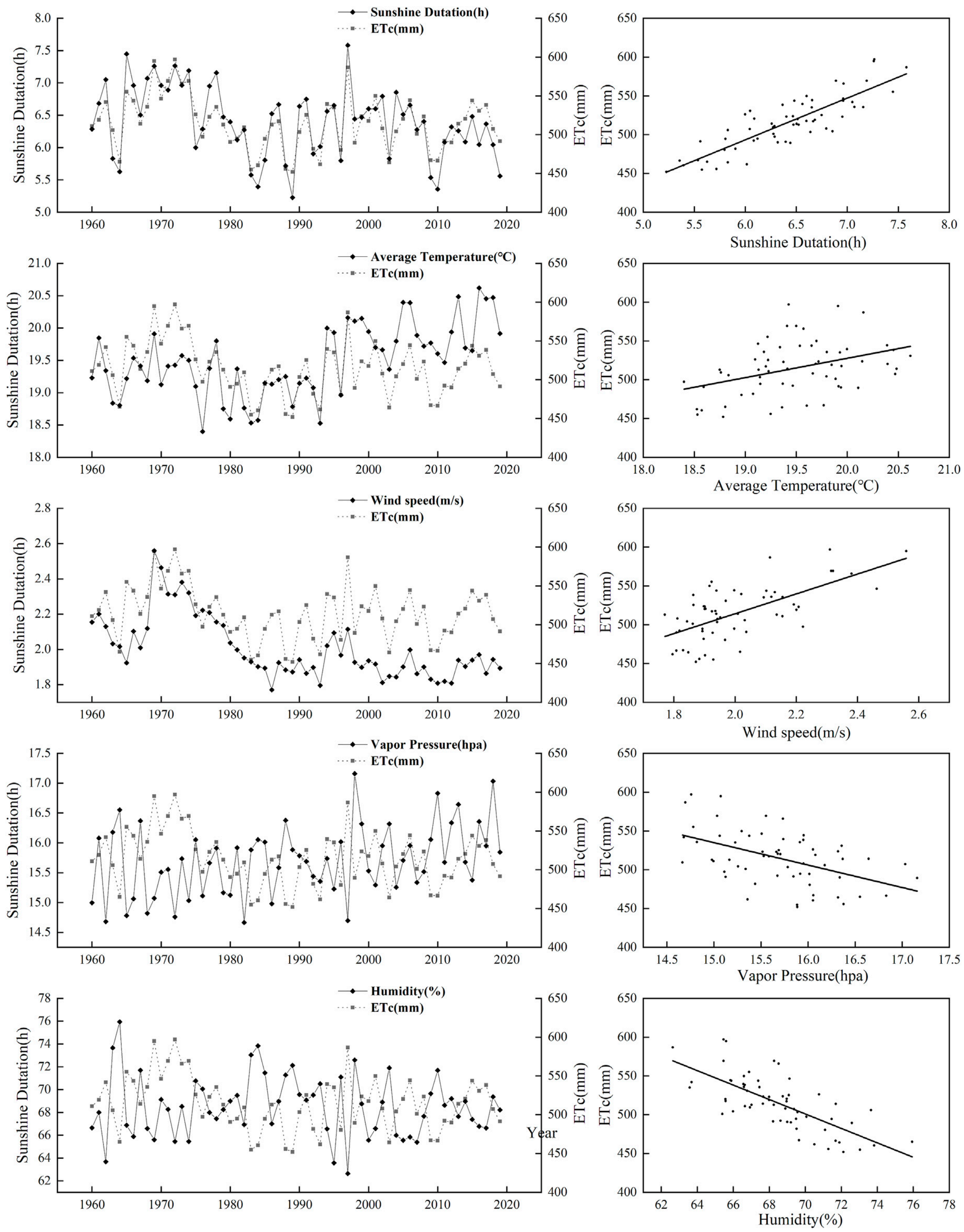

FIGURE 5
Trends in the transformation of maize water requirement and meteorological elements from 1960 to 2019.

vapor pressure and relative humidity, with correlation coefficients of −0.494 and −0.721, respectively. The sample data in this paper consisted of 60 groups, and the critical correlation coefficient value was calculated to be 0.254. The correlation coefficients of meteorological factors were all greater than the critical correlation coefficient value, indicating that the correlation between meteorological factors and maize water requirements was significant. Among them, sunshine hours, wind speed and

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TABLE 4 Analysis table of meteorological factors for the whole growth period.

		Northern Shaanxi		Guanzhong		Southern Shaanxi	
		I	II	I	II	I	II
Path coefficient	Sunshine	0.34	0.40	0.29	0.47	0.50	0.56
	Average temperature	0.20	0.41	0.35	0.64	0.24	0.42
	Wind speed	0.38	0.33	0.29	0.30	0.20	0.19
	Vapor pressure	−0.06	−0.28	−0.23	−0.46	−0.13	−0.27
	Humidity	−0.31	−0.05	−0.07	0.19	−0.11	0.08
Indirect coefficient	Sunshine	0.54	0.38	0.63	0.21	0.46	0.34
	Average temperature	0.43	0.29	0.48	−0.01	0.51	0.15
	Wind speed	0.30	0.29	0.46	0.25	0.68	0.61
	Vapor pressure	−0.60	−0.27	−0.46	−0.07	−0.32	−0.06
	Humidity	−0.52	−0.78	−0.85	−0.90	−0.75	−0.05
Decision coefficients	Sunshine	0.48	0.46	0.45	0.41	0.72	0.68
	Average temperature	0.22	0.41	0.46	0.39	0.30	0.30
	Wind speed	0.37	0.29	0.34	0.23	0.31	0.27
	Vapor pressure	−0.08	−0.23	−0.27	−0.27	−0.10	−0.11
	Humidity	−0.43	−0.07	−0.12	−0.31	−0.17	0.00

relative humidity were strongly correlated, while average temperature and water vapor pressure were moderately correlated. The trends in the transformation of maize water requirement and meteorological elements from 1960 to 2019 are shown in Figure 5.

Correlation analysis has confirmed that the meteorological factors selected in this paper are significantly correlated with maize water requirements, but the degree of correlation could not be determined. Multiple meteorological factors have a complex transfer process, and to further reveal the mechanism of each meteorological factor on maize water requirement, a more comprehensive analysis of the interaction between the variables is needed. In this paper, Shaanxi province was divided into three study areas according to topography and climate characteristics, and maize was divided into four growth stages according to its growth characteristics, and the direct and indirect effects of meteorological factors on maize water requirements in different regions and growth stages under time variation were understood by using path analysis to clarify the extent of their effects.

3.2.2 Path analysis

The results of the water requirement flux analysis for maize are shown in Tables 4, 5. From the analysis of the influence of meteorological factors on maize water requirement, the decision coefficients of sunshine hours, average temperature and wind speed were greater than zero, indicating that these factors promoted maize water requirement (positive factor), while the decision coefficients of water vapor pressure and relative humidity were less than zero, indicating that these factors inhibited maize water requirement (negative factor), regardless of the time stage, region and fertility stage. Among the positive factors, the promotion effect of sunshine hours and average temperature was the most obvious; the promotion effect of wind speed was comparatively obvious.

From the analysis of time nodes, the influence of sunshine hours, wind speed and relative humidity on maize water requirement in northern Shaanxi decreased with the change of time stages, which were 2.32%, 7.53%, and 35.32%, respectively, indicating that the promoting effect of sunshine hours and wind speed on maize water requirement and the inhibiting effect of relative humidity have been weakening in the last 30 years, and the influence of average temperature and water vapor pressure on maize water requirement has been increasing with a rise of 19.55% and 15.3%, respectively. The influence of wind speed and relative humidity on maize water requirement at each stage of reproduction was basically the same as that at the whole reproductive period, and the degree of influence was decreasing, while the influence of average temperature on maize water requirement at the jointing and male stages was increasing with time, but decreased by 10.17% and 21.63% at the seedling and maturity stages, respectively. The effect of water vapor pressure on the water requirement of the maize increased at the jointing, male and maturity stages, but decreased by 7.31% at the seedling stage.

In Guanzhong region, the promotion effect of meteorological factors on maize water requirement was decreasing, meaning that the effect of positive factors on maize water requirement was decreasing with time, while the inhibitory effect of negative factors was increasing, so maize water requirement was decreasing with time stage. The degree of influence of meteorological factors was inconsistent at different stages of fertility, for example, the contribution of sunshine hours to maize

TABLE 5 Analysis table of meteorological factors by growth stage.

		Seedling stage						Jointing stage						Male stage						Maturity					
		Northern Shaanxi		Guanzhong		Southern Shaanxi		Northern Shaanxi		Guanzhong		Southern Shaanxi		Northern Shaanxi		Guanzhong		Southern Shaanxi		Northern Shaanxi		Guanzhong		Southern Shaanxi	
		I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II
P	S	0.24	0.31	0.4	0.49	0.43	0.28	0.14	0.29	0.39	0.48	0.45	0.53	0.36	0.47	0.42	0.45	0.62	0.65	0.47	0.46	0.42	0.57	0.51	0.46
	A	0.52	0.48	0.49	0.42	0.68	0.7	0.11	0.39	0.33	0.22	0.33	0.31	0.18	0.32	0.11	0.58	0.67	0.91	0.56	0.39	0.28	0.17	0.52	0.74
	W	0.32	0.32	0.24	0.2	0.27	0.24	0.44	0.3	0.24	0.22	0.12	0.06	0.29	0.2	0.22	0.14	0.12	0.06	0.38	0.2	0.11	0.11	0.13	0.08
	V	−0.34	−0.25	−0.29	−0.43	−0.41	−0.43	0.12	−0.41	−0.18	−0.1	−0.14	−0.07	0	−0.15	0.08	−0.28	−0.39	−0.4	−0.64	−0.37	−0.13	0.09	−0.31	−0.4
	H	−0.35	−0.08	0.23	0.29	0.17	0.05	−0.57	0.11	−0.06	−0.16	−0.17	−0.24	−0.3	−0.11	−0.43	0.16	0.09	0.11	0.39	0	−0.25	−0.42	0.02	0.14
I	S	0.44	0.54	0.51	0.45	0.51	0.67	0.63	0.56	0.55	0.47	0.48	0.39	0.56	0.4	0.52	0.48	0.34	0.31	0.33	0.44	0.5	0.36	0.44	0.49
	A	0.28	0.24	0.35	0.41	0	0.08	0.43	0.35	0.53	0.53	0.48	0.38	0.54	0.49	0.7	0.25	0.11	−0.37	0.24	0.27	0.5	0.29	0.28	0.11
	W	0.17	0.14	0.55	0.48	0.25	0.54	0.32	0.24	0.59	0.58	0.51	0.65	0.55	0.31	0.77	0.93	0.16	0.15	0.17	0.22	0.43	0.39	0.52	0.49
	V	−0.31	−0.36	−0.54	−0.28	0.13	0.36	−0.86	−0.72	−0.29	−0.44	−0.38	−0.27	−0.87	−0.61	−0.57	−0.68	0.56	0.67	0.19	−0.26	−0.52	−0.3	0.18	0.38
	H	−0.52	−0.77	−1.18	−1.19	−1.01	−0.81	−0.24	−0.46	−0.84	−0.75	−0.72	−0.61	−0.65	−0.81	−1.25	−2.03	−0.99	−1.24	−1.23	−0.91	−0.71	−0.39	−0.92	−1.04
D	S	0.27	0.43	0.56	0.68	0.63	0.45	0.2	0.41	0.59	0.68	0.63	0.7	0.54	0.6	0.61	0.64	0.8	0.83	0.53	0.61	0.6	0.73	0.72	0.67
	A	0.56	0.46	0.59	0.53	0.84	0.6	0.11	0.42	0.47	0.29	0.43	0.33	0.22	0.41	0.16	0.63	0.59	1.5	0.58	0.36	0.36	0.13	0.55	0.7
	W	0.21	0.2	0.32	0.23	0.21	0.32	0.48	0.24	0.34	0.31	0.14	0.09	0.4	0.17	0.39	0.27	0.05	0.02	0.28	0.13	0.11	0.1	0.15	0.08
	V	−0.32	−0.25	−0.4	−0.43	0.06	−0.12	−0.19	−0.77	−0.13	−0.1	−0.12	−0.04	−0.01	−0.21	−0.09	−0.45	−0.29	−0.37	−0.03	−0.33	−0.15	−0.05	−0.01	−0.14
	H	−0.49	−0.13	−0.49	−0.6	−0.31	−0.08	−0.59	−0.09	−0.11	−0.26	−0.28	−0.35	−0.47	−0.18	−1.24	−0.61	−0.16	−0.26	−0.8	0.01	−0.42	−0.51	−0.03	−0.28

P: path coefficient; I: indirect coefficient; D: decision coefficients; S: sunshine; A: average temperature; W: wind speed; V: vapor pressure; H: humidity.

10.3389/fenvs.2023.1210256

water requirement was increasing at each stage of fertility, increasing by 11.67%, 8.81%, 2.39%, and 13.61%, respectively. The contribution of average temperature to maize water requirement was enhanced by 47.06% at the tasseling stage, but decreased at seedling, jointing and maturity stages decreased by 5.95%, 17.48% and 23.25%, respectively. It can be seen that meteorological factors have different effects on maize water requirements throughout the reproductive period and at different stages of fertility, and the sensitivity of different fertility stages to water is different. Therefore, the study by growth stage can better understand the changing trend of maize water requirement under climate change, which is of great significance for determining maize irrigation system and irrigation water.

The effects of sunshine hours, wind speed and relative humidity on maize water requirement in southern Shaanxi decreased with time, decreasing by 4.09%, 3.73% and 17.12%, respectively, indicating that the promoting effect of sunshine hours and wind speed on maize water requirement and the inhibiting effect of relative humidity are weakening. The influence of average temperature and water vapor pressure on maize water requirement is strengthening, increasing by 0.60% and 0.33%, respectively. This is directly related to the warming climate and increasing temperature. The promoting effect of sunshine hours on the water requirement of maize at the jointing and male stages was enhanced by 7.18% and 3.07%, while that at the seedling and maturity stages was reduced by 17.62% and 5.85%, respectively. The promoting effect of average temperature on the water requirement of maize at the tasseling stage was the greatest. The promoting effect of wind speed on the water requirement of maize at the seedling stage was the greatest. The inhibiting effect of water vapor pressure on the water requirement of maize at the tasseling stage was the greatest. The inhibiting effect of relative humidity on the water requirement of maize at the nodulation stage was the greatest.

From spatial distribution, for spring maize, the promoting effect of sunshine hours on maize water requirement gradually strengthened from north to south. The promoting effect of average temperature and wind speed gradually decreased from north to south. The inhibiting effect of water vapor pressure and relative humidity continuously decreased from north to south. In conclusion, the inhibitory effect of meteorological factors on the water requirement of maize gradually increased from north to south, while the promoting effect gradually decreased. That is, the water requirement of maize gradually decreased from north to south.

In summary, the meteorological factors are mutually binding and influencing each other. Sunshine hours and average temperature are the main meteorological factors affecting maize water requirement in Shaanxi Province, and they affect maize water requirement together with wind speed, water vapor pressure and relative humidity.

4 Discussion

This study points out that the overall trend of maize water requirement in Shaanxi Province is decreasing, and the spatial distribution is gradually decreasing from north to south with obvious spatial variability. This is because from north to south, Shaanxi Province gradually overflows into three climatic zones: temperate, warm temperate and north subtropical, with large differences in climate and significant differences in meteorological factors. In this study, the water requirement is calculated on the basis of meteorological conditions, so there is a large difference between the north and south values. In order to facilitate scientific irrigation, this paper divides maize growth into four fertility stages for study. The water requirement of maize at the fertility stage is the sum of daily water requirements, and the sowing time and duration of each fertility stage differ in different climatic zones, so the water requirement of the crop at different fertility stages also has significant differences. The division of maize growth time nodes in this paper was obtained from experimental studies by others and has been confirmed to be feasible (Liang et al., 2011; Li et al., 2015; Qin et al., 2016; Cheng et al., 2018).

The distribution of water resources in Shaanxi Province is more in the north and less in the north, but the distribution of water requirement is more in the north and less in the south, which indicates that spatial water transfer is needed for irrigation to meet crop growth requirements. The study of fertility stages can clarify the growth pattern of crops, and the high water requirement at the jointing stage indicates that irrigation should focus on timely irrigation at the jointing stage.

With the deepening influence of human activities on the natural environment, meteorological factors have obvious fluctuating variability over time. For example, the acceleration of climate warming process causes the average temperature to rise (Qin et al., 2014), and the excessive consumption of energy causes the serious phenomenon of haze (Tang et al., 2017), which further affects sunshine (Dale P and Yun, 2002). At the same time, the expropriation of land and the construction of tall buildings have a serious impact on air convection to some extent (Yi et al., 2021). Exploring the trends of crop water requirements in time series and the attribution analysis are important for agricultural irrigation and water resources allocation.

5 Conclusion

In this paper, PM formula and crop coefficient approach are used to calculate maize water requirement, and the water requirements of maize at each reproductive stage were comprehensively analyzed in terms of time series and spatial distribution. And the degree of influence of different meteorological factors on the maize water requirements was analyzed using the path analysis method. The main conclusions of this paper are as follows.

(1) The water requirement of maize in Shaanxi Province during the whole fertility period of 1960–2019 showed a decreasing trend. The water requirement of maize at each reproductive stage also showed a decreasing trend, with the most obvious decrease in maize water requirement at the maturity stage, with a change rate of −0.16 mm/a; followed by the jointing stage, with a change rate of −0.20 mm/a; and the rate of change at seedling stage is only −0.008 mm/a.

(2) From the trend of decreasing water requirement of maize in the last 60 years, it was found that 1989 was an inflection point, and the water requirement of maize showed a clear decreasing trend from 1960 to 1989 and a clear increasing trend from 1989 to 2019, so it was studied in two time periods. It was found that the multi-year average water requirement of maize was greater in

the first time period than in the second time period, with a decrease of 10.08 mm in the whole reproductive period and 0.31 mm, 3.59 mm, 2.06 mm and 4.00 mm in the seedling, jointing, male and maturity stages, respectively.

(3) The water requirement of maize decreased from north to south in the whole growth period. The water requirement at seedling stage and male stage was higher in the central part of the country, followed by the northern part and the southern part. The water requirement at jointing stage increased from north to south. The distribution of water requirement at maturity stage is higher in the north, second in the south and least in the Guanzhong area. The variation of maize water requirement with temporal stages had minimal effect on the overall trend of spatial distribution.

(4) There are some correlations between meteorological factors and maize water requirements, with sunshine hours, average temperature and wind speed positively correlated with maize water requirements, and water vapor pressure and relative humidity negatively correlated with maize water requirements. Among them, sunshine hours, wind speed and relative humidity were strongly correlated, while average temperature and water vapor pressure were moderately correlated.

(5) From the results of the path analysis, it can be seen that the average temperature and sunshine hours are the key factors influencing maize water requirement in Shaanxi Province, both by region and by time period, and have an enhancing effect on water requirement, while wind speed has an enhancing effect on water requirement but is not significant. And water vapor pressure and relative humidity have an inhibiting effect on water requirement.

Data availability statement

The data analyzed in this study is subject to the following licenses/restrictions: Data Availability Statement: Not applicable. Requests to access these datasets should be directed to JD, x20211010044@stu.ncwu.edu.cn.

Author contributions

Conceptualization: JD and JZ, Data curation: JD, GYS and FG, Formal Analysis: JD and JZ, Funding acquisition: JZ, Methodology: JD, JZ and GYS, Project administration: JZ, Resources: JD and JZ, Supervision: JZ, Validation: FG and GYS, Writing–original draft: JD, Writing–review and editing: JZ, FG and GYS. All authors contributed to the article and approved the submitted version.

Funding

This research was supported by the funds from the National Natural Science Foundation of China (52009042) and the Natural Science Foundation of Henan province (222300420231).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2023.1210256/full#supplementary-material

References

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M. (1998). *Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56*. Rome: FAO.

Babu, R. G., Veeranna, J., Kumar, K., and Rao, I. B. (2015). Estimation of water requirement for different crops using CROPWAT model in Anantapur region. *Asian J. Environ. Sci.* 9 (2), 75–79. doi:10.15740/HAS/AJES/9.2/75-79

Cao, H. X., Su, X. L., Kang, S. Z., and Wang, Z. C. (2008). Effect of climate change on main crop water requirements in guanzhong region. *J. Irrigation Drainage* (4), 6–9. doi:10.13522/j.cnki.ggps.2008.04.014

Cheng, K. L., Wei, J. C., and Jiang, C. J. (2018). Experiment on interplanting density of main maize varieties in Zhenba County. *Bull. Agric. Sci. Technol.* (10), 137–139.

China Statistical Publishing House (2022). *China statistical Yearbook*. Beijing: China Statistical Publishing House.

Chinese Ministry of Water Resources (2022). *China water resources bulletin*. Beijing, China: Chinese Ministry of Water Resources.

Jinger, D., Kumar, R., Kakade, V., Dinesh, D., Singh, G., Pande, V. C., et al. (2022). Agroforestry for controlling soil erosion and enhancing system productivity in ravine lands of Western India under climate change scenario. *Environ. Monit. Assess.* 194 (4), 267. doi:10.1007/S10661-022-09910-Z

Kaiser, Dale P., and Yun, Q. (2002). Decreasing trends in sunshine duration over China for 1954–1998: Indication of increased haze pollution? *Geophys. Res. Lett.* 29 (21), 1–38. doi:10.1029/2002GL016057

Kang, S. Z., Zhang, X. L., He, Z. Z., and Zhang, X. (1990). Research on the isoline map of corn water requirement and division of irrigation zone in Shaanxi province. *J. Water Resour. Water Eng.* (3), 19–34.

Kuwagata, T., Haginoya, S., Ono, K., Ishigooka, Y., and Miyata, A. (2018). Influence of local land cover on meteorological conditions in farmland, case study of a rice paddy field near tsukuba city, Japan. *J. Agric. Meteorology* 74 (4), 140–153. doi:10.2480/agrmet.D-18-00018

Li, H. M., and Fan, J. Z. (2015). Analysis on meteorological drought characteristics of Summer maize growing period in Guanzhong. *J. Shaanxi Meteorology* (4), 1–5.

Liang, W. Q., Can, H. J., and Wang, J. (2011). Experimental study on crop coefficient of maize in guanzhong region of Shaanxi province. *Water Sav. lrrigation* (12), 1–4.

Liu, H., Zhang, X. L., Wang, Y. X., Guo, Y., Luo, J. M., and Shen, Y. J. (2021). Spatio-temporal characteristics of the hydrothermal conditions in the growth period and various growth stages of maize in China from 1960 to 2018. *Chin. J. Eco-Agriculture* 29 (8), 1417–1429. doi:10.13930/j.cnki.cjea.201009

Liu, Y., Wang, L., Ni, G. H., and Cong, Z. T. (2009). Spatial distribution characteristics of irrigation water requirement for main crops in China. *Trans. Chin. Soc. Agric. Eng.* 25 (12), 6–12. doi:10.3969/j.issn.1002-6819.2009.12.002

Lu, J., Zhu, W. Z., and Gao, Z. Y. (2019). Review of toxicological effect of quantum dots on the liver. *Water Sav. Irrig.* 292 (12), 72–86. doi:10.1002/jat.3660

Luo, N. N., and Batur, B. (2017). Spatio-temporal variation of water requirement and meteorological impact factors of cotton in North Xinjiang, China. *Chin. J. Appl. Ecol.* 28 (10), 3305–3313. doi:10.13287/j.1001-9332.201710.028

Mthembu, S. G., Magwaza, L. S., Mashilo, J., Mditshwa, A., and Odindo, A. (2022). Drought tolerance assessment of potato (Solanum tuberosum L) genotypes at different growth stages, based on morphological and physiological traits. *Agric. Water Manag.* 261, 107361. doi:10.1016/J.AGWAT.2021.107361

Muneer, S., Xia, W. Y., Ming, Y. J., Faiz, M. A., Hao, J., Michael, I. T., et al. (2018). Regulated deficit irrigation impact at various growth stages and productivity of soybean. *J. Nat. Sci. Res.* Available at: https://www.researchgate.net/publication/326259184_Regulated_Deficit_Irrigation_Impact_at_Various_Growth_Stages_and_Productivity_of_Soybean 8 (12), 18–23.

Qin, D. H., and Thomas, S. (2014). Highlights of the IPCC working group I fifth assessment report. *Clim. Change Res.* 10 (1), 1–6. doi:10.3969/j.issn.1673-1719.2014.01.001

Qin, X. J., Wang, Y., and Huangpu, H. L. (2016). Comparative study on different sowing dates of spring maize in Weibei, Shaanxi Province. *Agric. Technol.* 36 (2), 77. doi:10.11974/nyyjs.20160133062

Ren, Y., Wang, Y. M., Chang, J. X., and Huang, Q. (2017). The spatial and temporal distribution of drought in Shaanxi province. *J. Nat. Resour.* 32 (1), 137–151. doi:10.11849/zrzyxb.20160166

Shang, M. F., Zhao, J. C., Han, T., Li, S., Wang, K. C., Gao, Z. Z., et al. (2022). Temporal and spatial variation of maize water requirement and water surplus and deficit in China from 1961 to 2020. *J. China Agric. Univ.* 27 (4), 22–30. doi:10.11841/j.issn.1007-4333.2022.04.02

Soleymani, A., and Shahrajabian, M. H. (2017). Assessment of ET-HS model for estimating crop water demand and its effects on yield and yield components of barley and wheat in semi-arid region of Iran. *Cercetari Agronomice Moldova* 50 (4), 37–49. doi:10.1515/cerce-2017-0034

Tang, D. L., Li, L., and Hong, X. F. (2017). The spatial spillover effect of energy consumption on haze pollution in China-An empirical research based on the static and dynamic spatial panel data model. *Syst. Engineering-Theory Pract.* 37 (7), 1697–1708. doi:10.12011/1000-6788(2017)07-1697-12

Wang, C., and Niu, W. Q. (2014). Effect factors and tendency of water demand and water use in guanzhong irrigation district. *J. Irrigation Drainage* 33 (3), 17–21. doi:10.13522/j.cnki.ggps.2014.03.004

Wu, M. H., and Wang, Y. (2023). Analysis of crop water demand and yield characteristics with their influencing factors in Shache irrigation area of Xinjiang. *Chin. J. Ecol.*, 1–13.

Xing, Z. X., Yu, Y., Li, F. Y., Wang, L. J., Fu, Q., and Wang, H. L. (2022). Change trend and key influencing factors identification of main crops water demand in jiansanjiang. *Trans. Chin. Soc. Agric. Mach.* 53 (7), 308–315+346. doi:10.6041/j.issn.1000-1298.2022.07.033

Xue, Y. R., Batur, B., Luo, N. N., Kang, L. J., and Wang, M. H. (2018). Climate response to water demand of cotton plant in growing seasonin tacheng prefecture. *Arid zone Res.* 35 (5), 1192–1198. doi:10.13866/j.azr.2018.05.24

Yi, X. C., Zhang, S. X., Shao, Z. F., Hua, Y. J., and Tang, J. (2021). Lnfluence of the height and density of stepped residential buildings on the urban wind environment. *Geomatics Inf. Sci. Wuhan Univ.*, 1–9.