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Spatial and Temporal Distribution Characteristics of Water Requirements for Maize in Inner Mongolia from 1959 to 2018

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Abstract: Crop water requirements are crucial for agricultural water management and redistribution. Based on meteorological and agricultural observation data, the effective precipitation (P_e), water requirements (ET_c), and irrigation water requirements (I_r) in the maize growing areas of Inner Mongolia were calculated. Furthermore, climatic trends of these variables were analysed to reveal their temporal and spatial distributions. The research results are as follows: the average P_e of maize in Inner Mongolia during the entire growth period was 125.9 mm, with an increasing trend from west to east. The P_e in the middle growth period of maize was the highest and was small in the early and late growth stages. The P_e climate exhibited a negative slope with a decreasing trend. The average ET_c of maize during the entire growth period was 480.6 mm. The high-value areas are mainly distributed in the Wulatzhongqi and Linhe areas. The average I_r of maize during the entire growth period was 402.9 mm, and the spatial distribution is similar to that of ET_c . In each growth period, I_r showed an increasing trend. Supplemental irrigation should be added appropriately during each growth period to ensure the normal growth of maize. This study can provide an effective basis for the optimisation of irrigation and regional water conservation in the maize cultivation area of Inner Mongolia.

Keywords: climatic trends; effective precipitation; water requirements; irrigation water requirements

1. Introduction

Climate change brings many significant challenges, and agriculture is considered to be one of the most vulnerable sectors to climate change [1–4]. In recent years, with the continuous intensification of the greenhouse effect, the problem of drought has become increasingly prominent, and agricultural water resources are facing serious challenges [5–7]. As water resources are mostly used in industrial applications, the remaining scope for agricultural water use is decreasing. Therefore, understanding spatial changes in crop water requirements in the context of climate change is conducive to crop irrigation system design and irrigation district planning. It can also provide a basis for studying the spatial distribution of crop water requirements and gaining an understanding of crop water consumption laws, agricultural water saving, and food security [8–10].

At present, many studies have been conducted on the spatiotemporal variation of the water requirements (ET_c) of different crops using the Penman–Monteith formula and the single crop coefficient method on a regional scale. The calculation of crop irrigation water requirements (I_r) by using the

difference between effective precipitation (P_e) and ET_c to guide agricultural water management has also been applied in many research areas [11–13]. Nie et al. (2018) [14] calculated and plotted the P_e , ET_c , and I_r of maize in Heilongjiang using a variety of methods including the CROPWAT model [15], the Mann–Kendall trend test, and spatial interpolation. Wang et al. (2016) [16] used meteorological data (1963–2012) from 54 meteorological stations in Xinjiang, in conjunction with the Penman–Monteith model and the crop coefficient recommended by *Food and Agriculture Organization Irrigation and Drainage Paper No. 56* (FAO-56) to calculate the ET_c for cotton at different growth stages, and used the Mann–Kendall test to analyse whether the crop's climatic trends revealed the spatial distribution of ET_c in cotton. Maize is one of the main food crops in Inner Mongolia. Determining the water requirements of crops in arid and semi-arid areas is crucial for agricultural water conservation.

At present, research on the ET_c of maize in Inner Mongolia is mostly concentrated on small, regional scales. For example, Yang et al. (2014) [17] studied the water balance relationship in the Xiliaohe River Basin, and Wang et al. (2018) [18] studied the ET_c of maize in drought years based on a 3 year field experiment in Tongliao City. Hou et al. (2016) [19] analysed the effect of water deficits on maize yield at different growth stages using the Jensen model. However, there has been less research on the water requirements of the whole maize planting area in Inner Mongolia.

This study aims to (1) quantitatively evaluate the spatial and temporal changes of P_e , ET_c , and I_r in different growth periods of maize from 1959–2018; (2) establish the relationship among the three according to the spatial variation of P_e , ET_c , and I_r slope; and (3) provide a scientific basis for optimising water resource allocation, effectively utilising agroclimatic resources, and regional sustainable development.

2. Materials and Methods

2.1. Overview of the Study Area

Inner Mongolia is located on the northern border of China (97–126° E, 37–53° N), with a land area of 1.183 million km², accounting for 12.1% of the national territory. It has a temperate continental climate, with rare precipitation, short summers, hot and rainy periods, long winters and cold and windy springs [20,21]. The annual number of hours of sunshine is generally more than 2700, with a maximum of 3400 h. The annual average wind speed is more than 3 m s^{−1}, and the landforms are distributed in a band from east to west or from south to north, which is inlaid with plains, mountains, and high plains, thus affecting the redistribution of water and heat conditions on the surface, resulting in unique natural conditions and resources. There are many types of crops in this area, among which maize is the primary crop.

2.2. Meteorological Data

All meteorological data were obtained from the China Meteorological Administration (CMA). The data used in the study were derived from 31 meteorological stations and 9 agro-meteorological observation stations for the period of 1959–2018 (Figure 1). The following variables were used: daily average temperature, maximum temperature, minimum temperature, average relative humidity, wind speed, precipitation, sunshine hours, elevation, and latitude and longitude. The agricultural meteorological observation index includes data on maize growth from 1991 to 2008. The distribution of agricultural meteorological observation in western Inner Mongolia is limited, and new agricultural meteorological observatories in the Hetao area were included. In this study, quality control of all weather stations was performed, weather stations with long-term meteorological data series were selected, and the missing values of meteorological data [22,23] were interpolated.

Figure 1. Distribution of weather and agrometeorological stations in Inner Mongolia.

2.3. Division of Maize Growth Period

In this study, the growth period was divided into four stages: (i) early growth: sowing to seven-leaf stage, (ii): rapid growth: seven-leaf to tassel stage, (iii) middle growth: tassel to milk-mature stage, and (iv) late growth: milk-mature to mature [24]. Based on the data from nine agricultural meteorological observation stations and assuming that the variety of maize remained unchanged during the study period, the date and days of each growth period of maize were determined. For meteorological stations without observational data from the growth period, the adjacent agrometeorological observation station data in the same climate zone were used. Table 1 shows the duration of the maize growth period and adjacent meteorological stations for each agricultural meteorological station.

Table 1. Duration of each growth period of maize and names of adjacent weather stations in each agrometeorological station from 1991 to 2008.

Agrometeorological Stations	L_{ini} (day)	L_{dev} (day)	L_{mid} (day)	L_{late} (day)	L_a (day)	Adjacent Site
Zhalantun	34	32	35	20	121	Ergun Youqi, Turi River, Hailar, Xiaoergou, Xin Barag Zuoqi, New Barag Youqi, Zhalantun
Tuquan	40	39	34	24	137	Suolun, Dong Ujimqin Qi
Jungar Banner	39	47	25	35	146	Darhan Muminggan United Banner, Siziwang banner, Huade, Baotou, Inner Mongolia, Hohhot, Jining, Dongsheng
Kailu County	39	46	27	29	141	Jarud Qi, Kailu
Tongliao	36	45	31	22	134	Tongliao
Wengniute Banner	37	51	40	22	150	Abag Qi, Xi Ujimqin Qi, Bairin Zuoqi, Xilin Hot, Linxi, Ongniud Qi
Chifeng	39	43	23	26	131	Duolun, Chifeng
Naiman Banner	43	43	31	18	135	Baogutu
Hetao area	31	38	48	28	145	Urad Zhongqi, Linhe, Otog Qi

Note: L_{ini} (early growth); L_{dev} (rapid growth); L_{mid} (middle growth); L_{late} (late growth); L_a (entire growth).

2.4. Test Indices and Methods

2.4.1. Effective Precipitation

The method recommended by the Soil Conservation Bureau of the United States Department of Agriculture was used to calculate effective precipitation (FAO, 1992), using the following equations:

$$P_e = \begin{cases} P(4.17 - 0.2P)/4.17 & (P \leq 8.3) \\ 4.17 + 0.1P & (P > 8.3) \end{cases} \quad (1)$$

where P is the daily rainfall (mm day^{-1}).

2.4.2. Calculation of Maize Water Requirements

The daily water requirement of maize during the growth period was calculated using the single crop coefficient method [24]. The water requirement in each growth period was obtained by summing the daily water requirements. The formula for this calculation is as follows:

$$ET_c = ET_0 \times K_c \quad (2)$$

where ET_c is the daily crop water requirements (mm day^{-1}), ET_0 is the daily reference crop transpiration (mm day^{-1}), and K_c is the crop coefficient.

According to the maize standard crop coefficient recommended by FAO-56, under the conditions of 45% minimum relative humidity, an average wind speed of $2 \text{ (m s}^{-1}\text{)}$, no water stress, and a high management level, the initial crop coefficient (K_{cini}), middle growth crop coefficient (K_{cmid}), and late growth crop coefficient (K_{cend}) attain values of 0.30, 1.20, and 0.35. Among them, the K_{cmid} of each agrometeorological observation station was revised, as shown in the following equation:

$$K_{cmid} = K_{cmid(tab)} + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)] \left(\frac{h}{3}\right)^{0.3} \quad (3)$$

where $K_{cmid(tab)}$ is the crop coefficient value recommended in FAO-56, u_2 is the average daily wind speed (m s^{-1}) at a height of 2 m during the middle crop growth period, RH_{min} is the average value of the minimum relative humidity during the middle crop growth day (%), and h is the average height of mid-growing crops (m).

The simplified form of the Penman–Monteith formula was used to calculate the reference crop water requirement (ET_0), thus:

$$ET_0 = \frac{0.408\Delta \times (R_n - G) + \frac{900\gamma \times U_2 \times (e_s - e_d)}{(T + 273)}}{\Delta + \gamma \times (1 + 0.34U_2)} \quad (4)$$

where ET_0 is the reference evapotranspiration (mm day^{-1}), T is the air temperature at 2 m height ($^{\circ}\text{C}$), Δ is the slope vapour pressure curve ($\text{KPa } ^{\circ}\text{C}^{-1}$), R_n is net radiation at the crop surface ($\text{MJ m}^{-2} \text{ day}^{-1}$), G is the soil heat flux density ($\text{MJ m}^{-2} \text{ day}^{-1}$), γ is the psychrometric constant ($\text{KPa } ^{\circ}\text{C}^{-1}$), e_s is the saturation vapour pressure (KPa), e_d is the actual vapour pressure (KPa), and U_2 is the wind speed at 2 m height (m s^{-1}).

2.4.3. Descriptive Statistics, Climatic Trends, Change Test, and Mapping

The coefficient of variation (Cv) is adopted to describe the temporal variability of the relevant elements, according to $Cv \leq 0.1$, $0.1 < Cv < 1.0$, and $Cv \geq 1.0$. These were defined as weak, medium, or strong [25].

A linear equation was used to fit the meteorological variables and to define the trends of the meteorological elements [26]:

$$X = a + bt \quad (5)$$

where X represents the fitted values of the meteorological elements, b represents the slope of the change in climate, t represents the corresponding year, and a represents the intercept. Thus, $b \times 10$ represents the slope of meteorological variables every 10 year.

The Mann–Kendall [27] test is a non-parametric test used to identify trends in a dataset. Because it has the advantages of simplicity and resistance to interference by outliers, it is often used to detect trends in a sequence. The Mann–Kendall test was used to analyse the P_e , ET_c , and I_r during the maize growing season. Positive and negative values of the standard normal system variable (Z) statistic indicate trends in the data. When the absolute value of Z is greater than or equal to 1.64, 2.32, and 2.56, it passes the significance test thresholds of 95%, 99%, and 99.9%, respectively. The statistical variables UF_k and UB_k were calculated and plotted to demonstrate the change and the year when the change began. In this approach, a neutral (0) sign, $Sgn(\dots)$, was used, which is defined as follows.

$$Sgn(X_j - X_k) = \begin{cases} +1 & (X_j - X_k) > 0 \\ 0 & (X_j - X_k) = 0 \\ -1 & (X_j - X_k) < 0 \end{cases} \quad (6)$$

where x_j and x_k are the time series values of n observations at the j th and k th moments, respectively. In addition, the Kendall sum statistic S is as follows:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n Sgn(X_j - X_k) \quad (7)$$

The monotonic trend can be judged according to the S value, variance, as follows:

$$Var(S) = n(n-1)(2n+5)/18 \quad (8)$$

when $n > 10$, another standard Z value is calculated, which is given as

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & S < 0 \end{cases} \quad (9)$$

When the Mann–Kendall test is further used to test sequence mutations, the test statistic is different from the above Z by constructing a sequence,

$$S_k = \sum_{i=1}^k \sum_{j=1}^{i-1} a_{ij} \quad (10)$$

where $k = 2, 3, 4, \dots, n$. Among them,

$$a_{ij} = \begin{cases} 1 & X_i - X_j \\ 0 & X_i = X_j \end{cases} \quad (11)$$

Considering $1 \leq j \leq i$, statistical variables are defined:

$$UF_k = \frac{[S_k - E(S_k)]}{\sqrt{Var(S_k)}} \quad (12)$$

where $k = 1, 2, \dots, n$. Thus,

$$E(S_k) = K(K+1)/4 \quad (13)$$

$$Var(S_k) = K(K+1)(2k+5)/72 \quad (14)$$

where UF_k is a standard normal distribution, given a significance level α , if $|UF_k| > U_{\alpha/2}$, which indicates that there is a significant trend change in the sequence. The time series X was arranged in reverse order and calculated according to the formula provided above.

$$\begin{cases} UB_k = -UF_k \\ k = n+1-k \end{cases} \quad (15)$$

where $k = 1, 2, \dots, n$.

By analysing the statistical sequence, the trend change of the sequence X can be further analyzed, and the time of the mutation can be clarified and the area of the mutation can be pointed out. If the UF_k value is greater than 0, it indicates that the sequence is on an upward trend; if it is less than 0, it indicates a downward trend; when they exceed the critical straight line, it indicates a significant upward or downward trend. If the two curves of UF_k and UB_k intersect, and the intersection point is between the critical straight lines, then the moment corresponding to the intersection point is the moment when the abrupt change begins.

The kriging interpolation method has the advantages of providing unbiased estimates and fully reflecting the spatial structure of variables; therefore, it is widely used in geographic analysis and meteorology. This study uses the kriging method that comes with the ArcMap 10.1 toolbox for spatial interpolation and plotting of P_e , ET_c , and I_r .

2.4.4. Irrigation Water Requirements

The difference between ET_c and P_e was used to determine whether irrigation was needed during the maize growing season. When P_e exceeded ET_c , irrigation was not required. Conversely, when P_e was less than ET_c , irrigation was required. The difference between ET_c and P_e was calculated as follows:

$$I_{rm} = \max\left(\sum_{i=1}^n ET_c - \sum_{i=1}^n P_e, 0\right) \quad (16)$$

$$I_{ra} = \sum_{i=1}^m I_{rm} \quad (17)$$

where n is the number of days in each growth period, I_{rm} is the Irrigation water requirement in the m th growth stage (mm), and I_{ra} is the total irrigation water requirement in the growth period (mm).

2.4.5. Degree of Coupling of Effective Precipitation and Water Requirement

The degree of coupling of crop water requirements and effective precipitation reflects the degree of utilisation of rainwater by the crop and is calculated using the following equation:

$$\lambda_i = \begin{cases} 1 & P_i \geq ET_{ci} \\ P_i / ET_{ci} & P_i < ET_{ci} \end{cases} \quad (18)$$

where λ_i is the degree of coupling of the i period of growth, P_i is the effective precipitation in the i period of growth (mm), and ET_{ci} is the water requirement of a crop in period i (mm).

2.4.6. Climate Classifications

The ratio of annual average precipitation to annual average potential evapotranspiration calculated by the Thornthwaite method can be used as a drought index. This method has been certified by the

United Nations Convention and is used globally in studies undertaken to combat desertification [28]. In terms of its climate, Inner Mongolia can be divided into severe-arid, arid, semi-arid, arid and semi humid, and humid and semi-humid, according to the criteria established by the United Nations Environment Programme. The severe-arid region is mainly in the western region of Inner Mongolia, the arid region mainly includes the central and western regions of Inner Mongolia, the semi-arid region mainly includes the central and middle eastern regions of Inner Mongolia, the arid and semi-humid region is mainly in the hilly area of northeast Inner Mongolia, and the humid and semi-humid areas are mainly in the eastern part of Inner Mongolia. Because the severe-arid area is not suitable for maize cultivation, few meteorological stations are located in this region; thus, it was not included in this study.

3. Results

3.1. Change of Effective Precipitation During the Maize Growing Period

3.1.1. Spatial and Temporal Changes of P_e in the Entire Growth Period of Maize

The spatial distribution of the average P_e of each meteorological station during the entire growth period of Inner Mongolian maize is shown in Figure 2a. The variation range was 59.1–166.7 mm, and the average value was 125.9 mm. High-value areas of P_e in Inner Mongolia, in which the average annual P_e exceeds 160 mm, are mainly distributed in the areas of the Turi River, Xiaoergou, Suolun, and Zhalantun. The low value areas, in which the annual average P_e is less than 82 mm, are mainly distributed in the areas of Urad Zhongqi and Linhe. The spatial distribution shows an increasing slope from west to east, with the lowest precipitation of 59.1 mm in Linhe and the largest value of 166.7 mm in the Turi River region. The temporal change of P_e during the entire growth period of Inner Mongolian maize from 1959 to 2018 is shown in Figure 3a. There was moderate variation with a minimum P_e of 77.8 mm (1966) and a maximum of 171.9 mm (1998). The spatial distribution of P_e slope at each station during the entire growth period of maize is shown in Figure 4a, and the variation range was between -4.96 and 1.77 mm decade $^{-1}$, with an average value of -1.26 mm decade $^{-1}$. Areas exhibiting a positive slope include meteorological stations such as Urad Zhongqi, Darhan Muminggan United Banner, Zhalantun, Dongsheng, Otog Qi, and Linhe. However, P_e was non-significant (Mann–Kendall test, $p > 0.05$) across the entire growing season. It can be seen from the curve UF that P_e has a slight increasing trend during 1984–2000. This turned into a decreasing trend after 2011, and it reached a significant level in 2011. The change date was 2006 (Figure 3d).

Figure 2. Spatial variation characteristics of effective precipitation (P_e) during the entire growth period (a), early growth period (b), rapid growth period (c), middle growth period (d), and end growth period (e) of maize from 1959 to 2018.

Figure 3. The temporal variation of P_e , water requirements (ET_c), and irrigation water requirements (I_r) during the entire growth period in Inner Mongolia and the abrupt test of the three. (a) The temporal variation of P_e ; (b) the temporal variation of ET_c ; (c) the temporal variation of I_r ; (d) P_e abrupt test; (e) ET_c abrupt test; (f) I_r abrupt test.

3.1.2. Spatial Variation of P_e in Each Growth Stage of Maize

The average annual P_e of Inner Mongolian maize during each growth period is shown in Figure 2b–e. At the beginning of the maize growing season, the average annual P_e of maize was 20.7 mm, ranging from 6.6 to 38.1 mm, and P_e increased from east to west. During the rapid growth stage of maize, the annual average P_e ranged between 13.4 and 66.3 mm, and the average P_e was 47.4 mm. In the middle stage of maize growth, the annual average P_e of each site ranged between 26.5 and 56.5 mm, with an average annual P_e of 38.9 mm, the spatial distribution was generally larger in the northeast region and was smaller in the other regions. In the late growth stage of maize, annual average P_e ranged between 8.6 and 34.9 mm, average annual average P_e was 18.8 mm, and a high value distribution was observed in the central and western regions. The average P_e of each growth stage of maize exhibited the following ranking from smallest to largest: late stage, early stage, middle stage, and rapid stage of maize growth. P_e was mainly concentrated in the rapid and middle growth periods, with a total of 86.3 mm, accounting for 68.61% of the average P_e across the entire growth season.

Figure 4. Spatial variation characteristics of P_e slope during the entire growth period (a), early growth period (b), rapid growth period (c), middle growth period (d), and end growth period (e) of maize from 1959 to 2018.

The slope of the annual average P_e in each growth stage of maize from 1959 to 2018 is shown in Figure 4b–e. At the beginning of the maize growth stage, the slope of P_e ranged from -0.13 to $2.55 \text{ mm decade}^{-1}$, with an average value of $0.80 \text{ mm decade}^{-1}$. Except for Baotou and Dong Ujimqin Qi, which were negative, other slopes for P_e were positive. The slope of P_e during the rapid growth period of maize ranged between -2.85 to $-1.38 \text{ mm decade}^{-1}$, with an average value of $-0.50 \text{ mm decade}^{-1}$. The slope of P_e in the middle growth period of maize ranged between -2.68 and $0.55 \text{ mm decade}^{-1}$, and the average was $-1.21 \text{ mm decade}^{-1}$. Except for Zhalantun and Tongliao, which exhibited positive slopes, the remaining sites exhibited negative slopes. The slope of P_e in the later growth period ranged between -1.15 and $1.47 \text{ mm decade}^{-1}$, with the average value of $-0.33 \text{ mm decade}^{-1}$. However, Urad Zhongqi, Otog Qi, Dongsheng, Linhe, Dahl hamming'an United banner, and Abag Qi exhibited positive slopes. Generally, P_e exhibited a positive slope in the early growth period of maize but exhibited a negative slope during the rapid and middle growth periods. The Mann–Kendall test showed that P_e increased significantly ($p < 0.05$) in the early growth period and decreased significantly ($p < 0.05$) in the middle growth period.

3.2. Change of Water Requirements During the Maize Growing Period

3.2.1. Spatial and Temporal Changes of ET_c in the Entire Growth Period of Maize

The spatial distribution of the average ET_c of each meteorological station during the entire growth period of Inner Mongolian maize is shown in Figure 5a. The annual average ET_c ranged between 268.1 and 777.8 mm, and the annual average ET_c was 480.6 mm. The high-value areas were mainly distributed in Urad Zhongqi and Linhe in Inner Mongolia. The annual average ET_c exceeded 600 mm, and the low-value areas were mainly distributed in Ergunayouqi, Xiaoergou, and Tulihe. The temporal change of ET_c during the entire growth period of Inner Mongolian maize from 1959 to 2018 is shown in Figure 3b. There was a weak variation, with a minimum ET_c of 412.1 mm (1959), and the

maximum was 544.8 mm (1972). The spatial distribution of the ET_c slope at each station during the entire growth period of maize is shown in Figure 6a, and the variation ranged between -9.88 and 16.60 mm decade $^{-1}$, with an average slope of 5.16 mm decade $^{-1}$. Overall, there was an upward trend. The high-value exceeded 13 mm decade $^{-1}$ in Linxi, Jining, Abag Qi, New Barag YouQi, and Hailar. The low value slopes occurred in the Otag Qian and Baotou areas, and exhibited slopes below -9 mm decade $^{-1}$. Among the sites, weather stations with a positive slope accounted for 84% of all weather stations. The Mann–Kendall test demonstrated that ET_c increased significantly ($p < 0.05$) during the entire growth period. During 1991–2006, the declining trend of ET_c was obvious, but not significant. After 2006, ET_c showed an increasing trend and reached a significant level in 2016, and the change date was 2002 (Figure 3e).

Figure 5. Spatial variation characteristics of ET_c during the entire growth period (a), early growth period (b), rapid growth period (c), middle growth period (d), and end growth period (e) of maize from 1959 to 2018.

3.2.2. Spatial Variation of ET_c in Each Growth Stage of Maize

The average annual ET_c of Inner Mongolian maize during each growth period is shown in Figure 5b–e. The initial ET_c of maize ranged between 38.8 and 77.8 mm, with an average of 60.0 mm. The annual average ET_c of the rapid maize growth period ranged between 78.8 and 230.5 mm, with an average of 167.1 mm. The spatial distribution of ET_c during the early growth and rapid growth period was generally higher in the western and central regions and lower in the northeast region. In the middle growth stage, the annual average ET_c ranged from 109.8 to 427.9 mm, with an average of 186.0 mm, and ET_c in the late growth stage ranged from 28.7 to 116.7 mm, with an average of 67.5 mm. The ET_c in the middle and late stages of fertility was generally larger in the western region and smaller in the central and eastern regions. The change in ET_c during the various growth periods of maize initially exhibited a rapid increase, followed by a decrease, with the maximum in the middle growth period. The sum of the rapid growth and middle growth period was 351.8 mm, accounting for 73.48% of the total ET_c .

Figure 6. Spatial variation characteristics of ET_c slope during the entire growth period (a), early growth period (b), rapid growth period (c), middle growth period (d), and end growth period (e) of maize from 1959 to 2018.

The change in the slope of annual average ET_c in Inner Mongolian maize during each growth period is shown in Figure 6b–e. The initial slope ranged from -0.84 to 2.18 mm decade^{-1} , with an average of 0.35 mm decade^{-1} ; generally, the slope increased. The rapid growth period slope ranged from -5.33 to 4.53 mm decade^{-1} , the average was 0.54 mm decade^{-1} , and the slope at middle growth ranged between -4.13 to 8.87 mm decade^{-1} , with an average of 3.46 mm decade^{-1} . The slope of ET_c in the later growth period ranged between -2.14 – 3.83 mm decade^{-1} , with an average of 0.82 mm decade^{-1} . The Mann–Kendall test demonstrated that the increase in ET_c in the middle and end stages of growth was highly significant ($p < 0.001$).

3.3. Change of Irrigation Water Requirements During the Maize Growing Period

3.3.1. Spatial and Temporal Changes of I_r in the Entire Growth Period of Maize

The spatial distribution of the average I_r of each meteorological station during the entire growth period of Inner Mongolian maize is shown in Figure 7a. The variation range was between 188.7 and 627.9 mm, with an average of 402.9 mm. The Urad Zhongqi and Linhe areas exhibited the largest values, whereas the Ergun Youqi, Xiaoergou, and Turi Rivers exhibited the lowest I_r values. The temporal change of I_r during the entire growth period of Inner Mongolian maize from 1959 to 2018 is shown in Figure 3c. There was moderate variation, with a minimum I_r of 316.7 mm (1959) and a maximum of 478.5 mm (1972). The spatial distribution of the I_r slope at each station during the entire growth period of maize is shown in Figure 8a, and the variation ranged between -9.56 and 20.67 mm decade^{-1} , with an average of 6.32 mm decade^{-1} . Outside of Baoguotu, Linhe, Hohhot, Baotou, and Otog Qi, the slopes of the other stations were positive. I_r increased significantly during the entire growth stage ($p < 0.05$). It can be seen from the curve UF that I_r showed a downward trend from 1991 to 2001 and did not reach a significant level. After 2003, I_r showed an increasing trend and reached a significant level in 2016, and the change date was 2001 (Figure 3f).

3.3.2. Spatial Variation of I_r in Each Growth Stage of Maize

The average annual I_r of Inner Mongolian maize during each growth period is shown in Figure 7b–e. In the early stage of maize growth, I_r ranged between 29.2 and 72.9 mm, with an average of 52.8 mm. I_r in the rapid growth period of maize ranged between 53.6 and 208.4 mm, with an average of 138.5 mm. In the early and rapid growth periods, the annual average I_r of maize tended to be larger in the central and western regions and smaller in the eastern region. The average annual I_r in the middle growth period ranged between 84.64 and 304.6 mm, with an average of 153.5 mm. The average annual I_r in the later growth period ranged between 21.2 and 101.9 mm, with an average of 58.1 mm. The average annual I_r in the middle and later stages of maize growth was larger in the western region and smaller in the central and eastern regions. The I_r was smallest in the early growth period, then initially increased and then decreased; thus, I_r was largest in the middle growth period.

Figure 7. Spatial variation characteristics of I_r during the entire growth period (a), early growth period (b), rapid growth period (c), middle growth period (d), and end growth period (e) of maize from 1959 to 2018.

The average annual I_r climatic trend rate of maize during each growth period is shown in Figure 8b–e. The slope of I_r in the initial growth period ranged between -1.15 and 2.06 mm decade $^{-1}$, with an average of 0.21 mm decade $^{-1}$. A small trend was apparent, with negative values accounting for 61.92% of the total. The slope of I_r during the rapid growth period ranged between -4.69 and 6.35 mm decade $^{-1}$, with an average of 1.12 mm decade $^{-1}$. The slope of I_r in the middle growth stage ranged between -3.93 and 10.44 mm decade $^{-1}$, with an average of 3.93 mm decade $^{-1}$, and the slope of I_r at the end of the growth period ranged between -1.97 and 3.78 mm decade $^{-1}$, with an average of 0.99 mm decade $^{-1}$. In the middle and late stages of growth, I_r increased significantly ($p < 0.05$).

Figure 8. Spatial variation characteristics of I_r slope during the entire growth period (a), early growth period (b), rapid growth period (c), middle growth period (d), and end growth period (e) of maize from 1959 to 2018.

3.4. Relationship Between P_e , ET_c , and I_r During Maize Growth

As shown in Figure 2, Figure 5, and Figure 7, ET_c decreased from west to east, and P_e increased from west to east, which inevitably leads to the same change in I_r as that observed for ET_c . This is due to the complementary relationship between P_e and I_r . During the early, rapid, and middle growing season, the majority of P_e was concentrated in the eastern and north-eastern regions. The differences in ET_c and I_r are consistent across growth periods: ET_c and I_r in the western region always maintained a higher range, whereas ET_c and I_r in the northeast region were smaller.

As shown in Figure 4, Figure 6, and Figure 8, for the western region, P_e showed a slightly increasing trend, and ET_c had a decreasing tendency. This indicates a potential to alleviate the relative lack of water in the western region. For the central and eastern regions, P_e showed a decreasing trend and ET_c showed an increasing trend, which lead to the obviously increasing slope of I_r . In the early growing period, ET_c only increased in some small areas, and P_e increased in the western and north-eastern regions. Therefore, I_r increased in the central region. In the rapid growth period, ET_c showed an obvious increasing trend in the central and eastern regions, and P_e showed a smaller increasing trend in the north-east region; therefore, I_r also showed an increasing trend in the central and eastern regions. In the middle growth, ET_c showed an increasing trend in the central region, and P_e showed an increasing trend in the western region, causing I_r to increase in the central and eastern regions, increasing significantly in Xilinhot, Abag Qi, and Linxi. At the end of the growing season, the increasing slope of ET_c was not obvious, and the increasing slope of P_e was not obvious in the northeast. Most the remaining areas exhibited a decreasing trend; thus, the slope of I_r is consistent with ET_c .

Figure 9 shows the changes of P_e , ET_c , and I_r at different growth stages across Inner Mongolia from 1959 to 2019. All variables initially increased and then decreased with crop development. The maximum values of ET_c and I_r appear in the middle growth period, but the maximum value of P_e appeared in the rapid growth period. The slope of P_e was only positive at the beginning of the growing season and was negative during other growth stages. The slopes of ET_c and I_r were positive for each growth period, reaching a maximum in the middle growth period. The ET_c in the middle growth

period increased significantly, whereas P_e showed a decreasing trend; thus, the increase in I_r during the middle growth period was greater.

Figure 9. Change in P_e , ET_c , and I_r at different growth stages in maize areas of Inner Mongolia from 1959 to 2019 and the climatic trends of each.

3.5. Characteristics of Water Requirements of Maize in Different Climatic Regions

To better study and compare the growth periods of P_e , ET_c , and I_r in different climate regions and the rules governing the coupling of P_e and ET_c , Inner Mongolia was divided into several climatic regions, and representative climate stations in each climatic region were selected for comparison. These stations include Linhe in the arid area, Chifeng in the semi-arid area, Zhalantun in the semi-arid and humid area, and Turi River in the humid and semi-humid area.

Changes in P_e at each weather station are ranked as follows in ascending order: Linhe, Chifeng, Zhalantun, and Turi River (Table 2). Both I_r and ET_c during the maize growth period changed as a function of the degree of drought—the higher the degree of drought, the higher the I_r and ET_c , and the change trend was opposite to that of P_e . As the climate zone changed from arid to moist and semi-moist, the degree of coupling of ET_c and P_e also increased. The degree of coupling of ET_c and P_e throughout the growth period was 0.09, 0.29, 0.45, and 0.62.

The degree of coupling of ET_c and P_e in different growth stages was less than 1, and water deficits were therefore apparent. The degree of coupling of ET_c and P_e in the arid area was less than 0.1, except for the end of the growing season, when it was 0.14. P_e in different growth periods of each weather station was less than ET_c . In arid and semi-arid regions, the degree of coupling of ET_c and P_e in different growth periods did not exhibit large changes; both were small.

The degree of coupling of ET_c and P_e changed from large to small and then to large values from the early growth to the end of the growth stages, with the smallest values in the middle growth stage, indicating severe water deficits. The largest degree of coupling of ET_c and P_e was apparent in the early growth stage; indicating a small water deficit.

Table 2. I_r , ET_c , P_e and their coupling degree at typical meteorological stations in different climate regions averaged over years.

Climate Zone	Weather Station	Project	L_{ini} (day)	L_{dev} (day)	L_{mid} (day)	L_{late} (day)	L_a (day)
Arid	Linhe	P_e (mm)	6.64	13.40	26.96	12.06	59.06
		ET_c (mm)	56.49	183.99	311.91	88.33	640.72
		I_r (mm)	53.99	174.22	290.64	81.69	600.55
		Coupling	0.07	0.07	0.09	0.14	0.09
Semi-Arid	Chifeng	P_e (mm)	23.62	56.49	29.86	19.50	129.47
		ET_c (mm)	69.52	171.72	129.66	80.66	451.54
		I_r (mm)	56.99	137.87	110.29	69.64	374.79
		Coupling	0.34	0.33	0.23	0.24	0.29
Arid and Semi-Humid	Zhalantun	P_e (mm)	36.51	54.27	52.33	18.59	161.70
		ET_c (mm)	51.35	100.40	163.40	41.86	357.01
		I_r (mm)	40.37	73.83	123.13	34.53	271.86
		Coupling	0.71	0.54	0.32	0.44	0.45
Humid and Semi-Humid	Turi River	P_e (mm)	36.57	52.83	56.48	20.88	166.76
		ET_c (mm)	38.80	78.78	121.79	28.70	268.07
		I_r (mm)	29.18	53.64	84.64	21.22	188.68
		Coupling	0.94	0.67	0.46	0.72	0.62

4. Discussion

In terms of ET_0 , Wang et al. (2015) [29] found that reference crop evapotranspiration (ET_0) was between 570 and 1674 mm from 1961 to 2010, and the highest value areas were distributed in western Inner Mongolia. Additionally, Tong et al. (2018) [30] noted that the average annual ET_0 in western Inner Mongolia was the largest, with values between 1300 and 1600 mm, and the ET_0 in Inner Mongolia from 1961 to 2010 in this study was between 567.4 and 1282 mm. Meteorological stations in the western region, and the western region per se were not within the scope of this study; thus, the highest ET_0 in Inner Mongolia in the present study was less than 1674 mm, the value reported in the former study. However, the minimum value was extremely close to that reported by Wang et al. (2015) [29].

Anon. (1993) [31] calculated the ET_c of 21 stations in the maize cultivation area of Inner Mongolia from 1961 to 1980 using the Penman formula and a single crop coefficient. The average value of ET_c in that study was 531.5 mm. The average water shortage was 280 mm. In the present study, the average value of water requirement ET_c from 1961 to 1980 was 481.6 mm; however the water shortage was 356.8 mm. Because K_c was divided and corrected in each growth period in the present study, and the former study applied a fixed value of K_c (0.8) when calculating ET_c , the average value of ET_c in the present study was 9.3% lower than that reported by Anon. (1993) [31]. In calculating the effective precipitation, the empirical coefficient method was used in the former study, but the method recommended by the USDA Soil Conservation Service was used in the present study. These two reasons ultimately led to the crop water shortage in this study being 76.8 mm higher than that of the former study.

The multi-year average I_r values in this study were 402.9 mm. The area with a large I_r was mainly located in the Urad Zhongqi and Linhe areas. For the Hetao Irrigation District, in which Linhe is located, the groundwater depth was relatively shallow, and this study did not consider the decrease in the irrigation amount caused by groundwater supplementation, nor did it consider the increase in the irrigation amount due to the serious harm of salinity in this area. Because of climate change, the temperature in Inner Mongolia increased at a rate of $0.45\text{ }^{\circ}\text{C decade}^{-1}$, and precipitation also decreased to varying degrees [32]. The Inner Mongolian maize sowing period has advanced by 1.0 d decade^{-1} on average, and the maturity period has been delayed by 3.3 d decade^{-1} , on average, and the whole growth period of maize has been extended by 4.5 d decade^{-1} . Moreover, due to the increase in accumulated temperature, the range of maize planting in Inner Mongolia has been expanded,

and maize varieties have also been converted to late varieties [33]. Therefore, calculations using crop production data from 1991 to 2008 may overestimate the value of ET_c in the first 30 years of 1959–2018. In this study, the effective precipitation P_e in the maize cultivation area of Inner Mongolia decreased at a rate of $-0.05 \text{ mm decade}^{-1}$, whereas the ET_c increased at a rate of $5.16 \text{ mm decade}^{-1}$. With the increase in temperature, the risk of drought will increase further [34].

5. Conclusions

This study used the single crop coefficient method and the spatial analysis function of ArcMap to calculate and plot the P_e , ET_c , and I_r in each growth period of maize in Inner Mongolia, and their respective climate gradients, to show the water supply requirement relationships of maize in Inner Mongolia.

During the growth period of maize in Inner Mongolia, P_e showed a downward trend, but ET_c showed an overall upward trend, indicating that the I_r of maize in Inner Mongolia will continue to increase in the future. North-eastern Inner Mongolia is rich in rainwater resources; as the temperature rises, the northeast will be more suitable for maize growth. Therefore, the scope of maize planting in the northeast can be appropriately expanded. For the western regions with greater demand for I_r , in addition to adopting water-saving measures such as deficit irrigation, mulching, and pipeline water delivery, appropriate adjustments should be made to the crop planting structure in western Inner Mongolia, such as reducing the range of maize sowing and increasing the number of crops that require less water and have higher economic benefits. The peak period of ET_c in maize is mainly in the rapid and middle growing period. In these periods, P_e shows a downward trend, whereas ET_c and I_r increase notably. Therefore, we should focus on supplementing irrigation in the rapid and middle growing periods for maize.

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