

Multi-Year Irrigation Frequency and Water Requirements During Typical Growth Stages for Winter Wheat and Summer Maize in Northern Henan (Postprint)

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Date: 2017-11-06T00:00:00+00:00

Abstract

Studying the changes in agricultural irrigation frequency under climate change scenarios in the Yubei region can provide references for local irrigation management and ensuring sustainable agricultural development. This study analyzes and processes meteorological data from the past 63 years (1951–2013) and soil data from the Xinxiang Qiliying station, combined with crop growth parameters, and establishes a drought irrigation index model by utilizing the relationships among precipitation, irrigation, crop evapotranspiration, and soil moisture. In this model, the Drought Irrigation Index (DII) is distributed between $[-1, 1]$, with values less than 0 indicating drought conditions requiring irrigation. Under the existing winter wheat–summer maize cropping system, the drought irrigation index model is used to calculate the multi-year drought irrigation index, and further derive the irrigation frequency. Three typical representative years for the winter wheat growing season were selected: wet (1985–1986), normal (2004–2005), and dry (1983–1984), and three typical representative years for the summer maize growing season: wet (2003), normal (1993), and dry (2009), to calculate the crop water requirements of winter wheat and summer maize under different representative years. Furthermore, the drought irrigation indices for winter wheat and summer maize under typical wet, normal, and dry representative years were calculated, and drought conditions with and without irrigation were analyzed. The results show that over the past 63 years, the winter wheat–summer maize system required 2–7 irrigations per year, with an average of 5.1 irrigations. The evapotranspiration (ETC) values for winter wheat under wet, normal, and dry representative years were 489.4 mm, 551.4 mm, and 481.7 mm, respectively, while those for summer maize were 466.1 mm, 477.8 mm, and 529.3 mm, respectively. Under non-irrigation conditions in typical

representative years, both winter wheat and summer maize experienced varying degrees of drought. After applying 2, 3, and 4 irrigations for winter wheat and 1, 2, and 3 irrigations for summer maize in typical wet, normal, and dry representative years, respectively, the impact of drought on their normal growth could be essentially eliminated. In summary, it is feasible to quantify irrigation frequency through the drought irrigation index. Under climate change scenarios, the irrigation frequency has varied significantly in the recent decade (2003–2013), with frequent interannual drought events, and better scientific irrigation management can reduce the impact of drought on crops.

Full Text

Multi-Year Irrigation Requirements and Analysis of Typical Growth Period Water Demand for Winter Wheat and Summer Maize in Northern Henan

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Abstract

Understanding changes in agricultural irrigation requirements under climate change scenarios is essential for local irrigation management and sustainable agricultural development in northern Henan. This study analyzed 63 years (1951–2013) of meteorological data and soil data from the Xinxiang Qiliying station, incorporating crop growth parameters to establish a drought irrigation index model based on the relationships among precipitation, irrigation, crop evapotranspiration, and soil moisture. In this model, the Drought Irrigation Index (DII) ranges from -1 to 1, with values below 0 indicating drought conditions that require irrigation. Under the existing winter wheat-summer maize cropping system, multi-year DIIs were calculated to determine annual irrigation frequency. Three representative years were selected for each crop: wet (1985–1986 for winter wheat; 2003 for summer maize), normal (2004–2005 for winter wheat; 1993 for summer maize), and dry (1983–1984 for winter wheat; 2009 for summer maize) growing seasons. Crop water requirements and DIIs were calculated for each representative year under both irrigated and rainfed conditions. The results showed that annual irrigation frequency for the winter wheat-summer maize system ranged from 2 to 7 times, averaging 5.1 times over the 63-year period. Evapotranspiration (ET_C) values for winter wheat in wet, normal, and dry seasons were 489.4 mm, 551.4 mm, and 481.7 mm, respectively; corresponding values for summer maize were 466.1 mm, 477.8 mm,

and 529.3 mm. Without irrigation, both crops experienced varying degrees of drought during typical growing seasons. However, irrigation applications of 2, 3, and 4 times for winter wheat and 1, 2, and 3 times for summer maize in wet, normal, and dry representative years, respectively, could effectively eliminate drought impacts on normal crop growth. In conclusion, using DII to quantify irrigation frequency is feasible. Under climate change, irrigation frequency fluctuated substantially during 2003–2013, with frequent interannual drought events, suggesting that improved scientific irrigation management is needed to reduce drought impacts on crop production.

Keywords: climate change; drought; winter wheat–summer maize cropping system; drought irrigation index; irrigation frequency; typical years

Introduction

Climate change has intensified the frequency of extreme weather events [1], with drought showing an increasing trend in both severity and occurrence in recent years [2–5]. Precipitation distribution is highly uneven across space and time in many regions of China, particularly in North China where low rainfall during critical winter wheat growth stages often triggers drought [6,7]. Agricultural drought is not merely a consequence of precipitation deficit; rather, it is influenced by multiple factors including soil available water content, crop root water uptake capacity, evapotranspiration, and irrigation [8]. Drought indices serve as quantitative measures of crop drought severity and have been widely studied and accepted. The Crop Water Stress Index (CWSI) [9] was proposed early on and has been widely applied to provide irrigation timing information [10–12]. CWSI ranges from 0 under fully irrigated conditions to 1 under severe water deficit, though the critical drought threshold is not easily distinguished. Additionally, CWSI calculation requires canopy temperature, which is difficult to monitor in practice [8].

Numerous studies have investigated irrigation scheduling, which primarily involves irrigation quotas, water amounts per application, irrigation frequency, and timing. Researchers have examined these aspects across different crops, regions, and methods [13–15]. For example, Shang et al. [16] studied winter wheat and summer maize as an integrated system in North China, simulating soil moisture dynamics to analyze irrigation schedules under different precipitation scenarios. They found that irrigation schedules differed from real-time irrigation needs due to precipitation and other meteorological factors. Similarly, irrigation schedules vary by region; for instance, wheat irrigation frequency and amounts in Minqin differ from those in North China [16–18]. Precipitation is a crucial factor affecting irrigation scheduling, and its uncertainty makes uniform irrigation regimes difficult to establish [16]. Wang et al. [14] used 30 years of precipitation data and Monte Carlo methods to simulate long-term decadal precipitation series, deriving different irrigation schedules for the Guangli irrigation

district. They found that with irrigation quotas of 60 mm, 120 mm, 180 mm, and 240 mm, irrigation frequencies were 2, 3, 4, and 6 times, respectively, with high-yield probabilities of 1%, 12%, 62.8%, and 98.8%. Moreover, precipitation uncertainty complicates drought prediction [2]. Integrating meteorological information with crop water requirements can help predict drought conditions to some extent [3]. Ozelkan et al. [19] used the Standardized Precipitation Index (SPI) and Normalized Difference Vegetation Index (NDVI) to analyze drought conditions for irrigated and rainfed crops in Turkey, finding drought indices feasible for agricultural drought monitoring. Additionally, previous studies using the CERES-Wheat model in DASST indicated that spring wheat should be irrigated when soil moisture drops to 65% of field capacity; otherwise, yield would be affected. This 65% threshold can serve as a critical point for determining irrigation need. In the Huang-Huai-Hai region, the winter wheat-summer maize rotation is the dominant cropping system [20,21]. However, models for determining irrigation schedules for these two crops have issues with simulation accuracy and practical applicability [16,22]. Recent climate change studies indicate that extreme drought events are increasing in frequency, making prediction more challenging [23]. In some regions, precipitation during the winter wheat growing season shows a decreasing trend, while summer maize season precipitation is increasing, creating a “worse drought and worse flooding” scenario [7,24,25].

Current irrigation scheduling methods can no longer accurately guide production under climate change, yet drought remains the primary trigger for irrigation [26]. However, few studies have examined how irrigation schedules change under climate change. In practice, irrigation authorities and farmers primarily focus on irrigation frequency, which can be conveniently and accurately determined through drought indices. Therefore, this study established a drought irrigation index based on water balance principles, considering relationships among soil moisture, evapotranspiration, precipitation, and irrigation to clarify irrigation timing and determine required irrigation frequency. Using hydrometeorological data from 1951-2013 and analyzing representative dry, normal, and wet years, this paper: (1) proposes a drought irrigation index; (2) calculates annual irrigation frequency under the winter wheat-summer maize system from 1951-2013; and (3) compares and analyzes drought irrigation requirements for winter wheat and summer maize during different typical growth periods. Clarifying long-term changes in irrigation frequency provides a reference for Yellow River water diversion and irrigation scheduling in the study region.

1.1 Study Area

The study area is located in the People’s Victory Canal irrigation district and surrounding regions in Xinxiang City, northern Henan Province, situated on the alluvial plain north of the Yellow River at an elevation of 73 m. The region has a temperate monsoon climate with an average annual precipitation of 562.21 mm and mean annual temperature of 14.46 °C (1951-2013). Precip-

itation is concentrated from June to September. The main crops are winter wheat and summer maize. Irrigation schedules vary by hydrological year type; normally, winter wheat receives 3–4 irrigations, while summer maize typically receives none. Irrigation water primarily comes from Yellow River diversion and groundwater.

1.2 Data Sources

Data used in this study include meteorological data, soil data, and crop coefficients. Meteorological data comprise daily surface observations from the Xinxiang weather station (China Meteorological Data Center) for 63 years (1951–2013), including daily maximum and minimum temperatures, precipitation, wind speed, sunshine hours, vapor pressure, relative humidity, and mean temperature. Precipitation distribution for the Xinxiang station from 1951–2013 is shown in [Figure 1: see original paper].

Crop coefficients (K_c) for winter wheat and summer maize in northern Henan were obtained from reference [27], with monthly mean values presented in . Soil data were collected from representative fields in the study area in May 2013, with six soil samples taken from 0–1 m depth to measure particle composition. As the region is a Yellow River alluvial plain with relatively uniform soil texture, particle composition is shown in . Using USDA classification, the soil was identified as sandy loam. Soil moisture content before and after irrigation was measured using the oven-drying method, and field capacity was determined as 28% using the double-ring infiltrometer method [28]. Considering the wilting coefficient and crop root water uptake difficulty, effective available soil water within the 1 m root zone was 120 mm.

1.3 Drought Irrigation Index Model

Based on soil water balance principles and considering relationships among crop evapotranspiration, precipitation, irrigation, and soil available water, a drought index model was established to track temporal changes, with the goal of meeting crop water demand. When precipitation and soil available water cannot meet crop evapotranspiration, water stress occurs, indicating drought that requires irrigation to alleviate and ensure normal crop growth during prolonged dry periods [17,26].

The model uses the following equations:

$$\theta = \frac{P - ET_C + I + SW_A}{SW_A}$$

where θ is the relative value of soil water available for crop uptake within the effective root depth at a given time; P is precipitation (mm); ET_C is evapotranspiration (mm); I is irrigation (mm); and SW_A is soil available water, defined as

the difference between soil water content and wilting coefficient at 65% [17,22] (mm).

ET_C is calculated using Equation (2) with the Penman-Monteith formula to compute ET_0 (potential evapotranspiration):

$$w = \frac{d\theta}{dt} = \frac{P - ET_C + I}{SW_A}$$

where w is the temporal change in θ from t_i to t_{i+n} , with daily time steps, and i represents the i th day of the crop growth period ($i > 0$). P_i is precipitation on day i (mm); ET_{C_i} is evapotranspiration on day i (mm); and I_i is irrigation on day i (mm).

$$DII = \frac{P - ET_C + I}{SW_A} = w - 1$$

where DII is the drought irrigation index, with values ranging from -1 to 1. When $DII < 0$, soil available water cannot meet crop water demand, indicating drought and the need for irrigation.

This study analyzed both rainfed and irrigated scenarios. The rainfed scenario assumed no irrigation, analyzing potential drought conditions during the growth period to determine drought frequency. The irrigated scenario applied irrigation when $DII < 0$, replenishing soil moisture to field capacity. As crops grew and evapotranspiration consumed soil water, subsequent $DII < 0$ events indicated recurring drought and irrigation need. This process was used to determine irrigation frequency and annual requirements. Data were processed using Microsoft Excel and Origin.

2 Results and Analysis

2.1 Multi-Year Irrigation Frequency for Winter Wheat-Summer Maize System Using 1951-2013 data, the drought irrigation index model calculated annual irrigation frequency for the winter wheat-summer maize system, shown in [Figure 2: see original paper]. Annual irrigation frequency mostly ranged from 4 to 6 times, averaging 5.1 times over 63 years. Seven extremely dry years required 7 irrigations (1959, 1965, 1966, 1968, 1997, 2001, and 2002), while three relatively wet years required only 2 irrigations (1964, 1990, and 2003). Since the 1990s, interannual irrigation frequency fluctuation has intensified, likely due to climate change increasing extreme weather events [29]. Climate change has affected irrigation frequency over the 63-year period, with the following sections focusing on DII analysis for three typical growth periods.

2.2 Water Demand Characteristics in Typical Growth Periods Using meteorological data corrected for snow, ice, hail, frost, dew, and wind speed, three representative growth periods were identified at probability levels of $P = 75\%$, 50% , and 25% for dry, normal, and wet conditions [30]. For winter wheat (growth period spanning calendar years), representative periods were: wet (1985–1986), normal (2004–2005), and dry (1983–1984), with an average growth duration of approximately 240 days (sowing around October 10, harvest around June 5). Precipitation distributions for these periods are shown in [Figure 3: see original paper]. For summer maize (growth period <4 months), representative periods were: wet (2003), normal (1993), and dry (2009), with an average duration of approximately 100 days (sowing around June 10, harvest around September 17). Precipitation distributions are shown in [Figure 4: see original paper].

Calculated ET_C values are presented in [Figure 5: see original paper]. While ET_C varied among the three representative periods for each crop, overall trends were consistent. For winter wheat ([Figure 5: see original paper]a), ET_C increased slowly from sowing in October until December, with greater fluctuation in the normal period compared to wet and dry periods. The lowest ET_C occurred during the overwintering period (70–108 days after sowing), after which ET_C gradually increased from green-up to milk ripening. Total winter wheat ET_C ranked as: normal > wet > dry period.

For summer maize ([Figure 5: see original paper]b), ET_C showed fluctuating increases and decreases, reflecting interactions between crop development and meteorological factors. Total summer maize ET_C ranked as: dry > normal > wet period.

2.3 Drought Irrigation Index for Winter Wheat DII for rainfed winter wheat is shown in [Figure 6: see original paper]a, where $DII < 0$ indicates drought. Without irrigation, all three representative periods experienced drought of varying durations and severities. The wet period had approximately 50 drought days, concentrated in the critical jointing to heading stage (around 165 days after sowing) when water demand is high. The normal period had about 85 drought days, beginning around day 148 and continuing until harvest, with a brief one-week relief around days 220–227. The dry period experienced approximately 190 drought days, with wheat remaining in drought after day 40, except for a temporary relief from one precipitation event around day 150.

Post-irrigation DII is shown in [Figure 6: see original paper]b. The wet period required 2 irrigations: one at jointing (around day 165) and one at heading (day 200). The normal period required 3 irrigations at days 146, 185, and 205. The dry period required 4 irrigations: an overwintering irrigation around day 37, plus applications at days 152, 192, and 220. These irrigation schedules effectively eliminated drought while allowing brief water deficits to stimulate physiological processes and enhance crop vigor [31].

2.4 Drought Irrigation Index for Summer Maize Rainfed summer maize drought conditions are shown in [Figure 7: see original paper]a. Without irrigation, all three representative periods experienced drought: approximately 25 days in the wet period, 37 days in the normal period, and 58 days in the dry period. In the wet period, drought occurred immediately after sowing (due to high temperatures and delayed rainfall) for about 10 days, recurred around day 20 for another 10 days, and appeared again around day 70 for approximately 5 days. In the normal period, a 10-day drought began around day 8, followed by drought around days 60–70 that was temporarily relieved, after which drought persisted until maturity. In the dry period, post-sowing drought lasted about 30 days, followed by intermittent drought from day 50 to maturity with four episodes of 6–9 days each.

Post-irrigation *DII* is shown in [Figure 7: see original paper]b. Wet, normal, and dry periods required 1, 2, and 3 irrigations, respectively, to eliminate drought. The wet period needed one irrigation at sowing when precipitation was low and evapotranspiration was high. The normal period required irrigation at sowing and around day 60. The dry period needed irrigation at sowing and at approximately days 20 and 62. Summer maize growth periods experience concentrated, high-intensity rainfall that can cause waterlogging, requiring timely drainage to avoid flood damage.

Discussion

In the three representative precipitation years, winter wheat total ET_C ranked as normal > wet > dry period, while summer maize ranked as dry > normal > wet period. Wet years had more summer rainfall days, lower sunshine hours, and higher humidity, resulting in lower crop evapotranspiration and soil evaporation. Dry years had higher ET_C than normal and wet years for summer maize. For winter wheat, which includes an overwintering period with minimal soil evaporation, dry years had the lowest total ET_C because surface soil moisture was lower, reducing both soil and crop evaporation. In wet years, high humidity and low sunshine resulted in lower calculated ET_C for winter wheat compared to normal years. The specific mechanisms require further investigation.

In the North China Plain's winter wheat–summer maize rotation system, precipitation cannot meet crop water requirements in dry, normal, or wet representative years, necessitating irrigation for normal crop development, consistent with findings by Wang et al. [14], Zhang et al. [15], and Sun et al. [7]. This study found an average of 5.1 irrigations annually for the rotation system, with winter wheat requiring 2, 3, and 4 irrigations and summer maize requiring 1, 2, and 3 irrigations in wet, normal, and dry years, respectively, aligning with previous research [7,13–14,21–31]. Without irrigation, crops experience annual drought stress. While moderate drought stress can improve crop quality and stimulate water uptake potential [22,30], prolonged drought reduces yield. Natural precipitation rarely meets crop water demands temporally and spatially [24,25]. Although summer maize receives abundant rainfall, uneven temporal

distribution can cause drought during critical growth stages, explaining why irrigation is needed despite total precipitation exceeding crop requirements.

Determining irrigation quotas and water amounts per application is crucial for irrigation scheduling. This study shows that annual precipitation and drought conditions vary, making uniform irrigation quotas difficult to establish. Many studies focus on irrigating at key growth stages, as ensuring adequate water during critical periods substantially reduces drought impacts [17-18]. However, this approach differs from our results because drought timing does not always coincide with key growth stages. The key difference lies in accurately identifying drought timing. Drought indices effectively quantify drought [26-31]. The *DII* developed here, like CWSI [8-9] and the index by Shi et al. [26], reliably identifies crop water deficit timing. Our *DII* emphasizes the ratio of crop water demand to soil available water, triggering irrigation when soil moisture cannot meet crop needs, improving upon methods using a single soil moisture threshold.

This study constructed a crop drought index using 1951-2013 meteorological data and observations from northern Henan, providing regional reference value, though broader representativeness requires further validation. Our irrigation frequency results generally align with previous research and local experience. Future studies should strengthen investigations of climate change impacts on irrigation and refine methods for identifying optimal irrigation timing. When *DII* shows consecutive negative values, crops enter severe drought requiring irrigation; occasional deficits can regulate crop water status and stimulate growth potential, though the appropriate duration of drought stress requires further research.

Conclusion

Analysis of *DII* from 1951-2013 revealed annual irrigation frequencies of 2-7 times, mostly 4-6 times, with 7 irrigations needed in the driest years. Winter wheat requires 4 irrigations in dry years for normal growth, while summer maize needs 3 irrigations in dry years despite abundant seasonal precipitation due to temporal imbalance.

Representative period analysis demonstrated that wet, normal, and dry years all experienced drought requiring irrigation for normal crop growth. Winter wheat needed 2, 3, and 4 irrigations, while summer maize needed 1, 2, and 3 irrigations in wet, normal, and dry representative periods, respectively, to effectively mitigate drought impacts.

The Drought Irrigation Index serves as an effective crop drought indicator that accurately identifies irrigation timing, providing valuable guidance for crop irrigation management.

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