STUDY ON SOYBEAN WATER DEMAND AND IRRIGATION SCHEDULE IN WESTERN HEILONGJIANG PROVINCE BASED ON CROPWAT MODEL

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Abstract. This scientific research has determined the water demand of soybean in different hydrological years to overcome problems such as the lack of water for the growth and development of grain crops. Water shortage is caused by low precipitation in the western part of Heilongjiang Province and the high incidence of drought. Drip irrigation, sprinkler irrigation and other irrigation models and irrigation systems were established and the impact of climate change on the water demand law of soybean growth was analyzed in the semi-arid areas in the western part of Heilongjiang Province. According to the meteorological data of Heshan Farm of Heilongjiang Province's Jiusan Administration Bureau from 1951 to 2018, the main parameters of soybean crop growth and the field soil layer data, the Mann-Kendall development trend test method was used to analyze the change trend of climate factors during the soybean growth period, and the CROPWAT model was used to analyze the change trend of water demand, effective rainfall and irrigation water flow throughout the year and each growth period. On this basis, the coupling degree of effective rainfall and soybean growth demand in different hydrological years was compared, and the corresponding irrigation scheme was determined. The results showed that the monthly average temperature in the whole growth period of soybean increased significantly, while the monthly average wind speed decreased significantly, and the demand for soybean decreased with the rate of 9.15 mm/10 years. The water consumption in the wet year was 396.06 mm, the water consumption in the normal year was 390.65 mm, the water consumption in the dry year was 420.21 mm, and the water consumption in the dry year was 459.96 mm. In different hydrological years, the coupling degree of local effective rainfall and soybean water demand shows a trend of increasing first and then decreasing. Under sprinkler irrigation conditions, the irrigation quota was 68.4 mm in the normal year, 121.1 mm in the dry year and 175.9 mm in the extremely dry year. Under the condition of drip irrigation, the irrigation quota in the normal year was 66.3 mm, the irrigation quota in the dry year was 111.6 mm, and the irrigation quota in the extremely dry year was 151.5 mm. According to the irrigation quota under different irrigation conditions, the effective rainfall in other hydrological years in the region is difficult to meet the water demand for soybean growth, except for the wet and flat years. Therefore, in different hydrological years, proper irrigation should be carried out at the flowering and podding stages of soybean to ensure high and stable yield.
Keywords: *soybean, hydrological year, water demand, irrigation system, CROPWAT mode*

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Introduction

The western region of Heilongjiang Province is the most important commercial grain base and major soybean producing area in Heilongjiang Province and in the whole country, with the western soybean planting area of nearly 30 million mu in 2019 (Liu and Xu, 2011). The frequent occurrence of spring drought has seriously affected the planting and seedling growth and development of soybeans in the region, and supplementary irrigation is one of the important measures to achieve its sustained stable yield and high yield, so it is of great significance to carry out scientific research on the water demand of soybean growth under altered environment due to the climate change in the western region of Heilongjiang Province, which is of great significance for formulating a reasonable and effective irrigation system in China's agricultural production, ensuring food security and realizing efficient utilization of water resources (Huang et al., 2015). In recent years, Chinese and other foreign scholars have carried out a lot of research on the impact of climate change on crop water demand. Ren et al. (2020) studied the water demand and drought and flood trends of maize during the 60-year growth period in Northeast China and found that the water demand of maize in the growing period and four growth stages was not obvious. Zhang et al. (2009) studied the water demand of northeast maize by climate change and believed that the growth and water demand of northeast maize is likely to increase from the average percentage in the future. Huang et al. (2019) analyzed the key climatic factors affecting crop water demand in Minqin area from 1968 to 2018 and found that the most important climatic factors that caused the interannual change of water demand of reference crops in the region were maximum temperature and annual average relative air humidity. Nie et al. (2018) scientifically analyzed the spatiotemporal distribution characteristics of maize growth and water demand and drought in Heilongjiang Province in the past 50 years, and found that the frequency distribution of drought and the spatial distribution of water demand were basically the same in different growth periods of maize, and the frequency of drought in the early growth and rapid development periods was high, and spring drought and summer drought were prone to occur. Previous scientific research mainly used the Mann-Kendall trend analysis method to analyze the water demand of crops on a large scale, but due to climatic conditions, soil structure, tillage technology and other factors will affect the water demand of the crop itself, it is difficult to apply the above research results in the local environment and specifically guide production.

At present, sprinkler irrigation and drip irrigation are two water-saving irrigation technologies that are efficient and practical to supplement the water content in the crop growth environment (Shi et al., 2006; Wang, 2010), Sprinkler irrigation and drip irrigation have the characteristics of water saving, time saving, labor saving and high efficiency, and have been used on a large scale in crop growth irrigation. Among them, sprinkler irrigation can effectively control the amount of irrigation water and uniformity, will not cause ground loss and deep leakage, can effectively control soil moisture, gas, thermal energy, nutrients, and microbial status, etc., and can also adjust the spraying amount according to the demands of crops, which can save 30-50% of irrigation water compared with the traditional irrigation mode. Drip irrigation is a type of local irrigation that ensures that the water in the root area of the crop is properly replenished, further improving the use of water resources. By effectively combining irrigation and fertilization, an appropriate amount of chemical fertilizer can be directly applied to the roots of crops to achieve the purpose of water and fertilizer integration. This can greatly improve the effective utilization rate of chemical fertilizer, save the overall amount of chemical fertilizer, and reduce environmental pollution. At present, the integration of water and fertilizer has been widely used in the planting of corn, soybean, cotton, and other crop species (Liu et al., 2008; Feng et al., 2011; Zhang et al., 2016).

The CROPWAT model is a decision analysis tool developed by the Food and Agriculture Organization of the United Nations (FAO), and its calculation procedure is based on the series of documents published by the Food and Agriculture Organization of the United Nations "Guidelines for Crop Water Requirements" (FAO-56) (Smith, 1992; FAO, 1998). The tool can calculate the amount of water suitable for crop growth and irrigation for different meteorological data, soil layer data information, crop types and other information, simulate the relationship between crop yield and water in rainfed and irrigation environments, and then formulate the most suitable irrigation scheme for crop growth, and the model has been applied in many countries and regions around the world (Chen et al., 2012; Wu et al., 2015; Bai et al., 2017).

Based on the meteorological data, main parameters of soybean crops and on-site soil layer data information of Heshan Farm of Jiusan Management Bureau of Heilongjiang Province from 1951 to 2018, this scientific research used the Mann-Kendall development trend test method to reasonably analyze the changes of meteorological factors during the soybean growth period, and applied the CROPWAT model to analyze the changes of water demand, effective rainfall and irrigation water at each growth stage of soybean, and established the change trend and reasons of soybean growth water demand. In addition, the coupling degree of growth water demand and effective rainfall of soybeans of different hydrological years was compared, so as to formulate an irrigation scheme that could ensure high and stable soybean yield (Ma et al., 2012; Chu et al., 2015; Zhang et al., 2019; Wang et al., 2020).

Research area and methodology

Overview of the study area

Heshan Farm Science and Technology Park (48°43'~49°03'N, 124°56'~126°21'E) was selected as the research area, which is located in the west of Heilongjiang Province, is a typical high-latitude, low-calorie dryland agricultural area, with an annual average temperature of ≥ 10 °C, an annual effective accumulated temperature of 2000 °C~ 2300 °C, a frost-free period of 115~ 120d, a multi-year average wind speed of 4m/s, and a windy and arid spring. The local soil texture is dominated by black soil, agricultural land is weakly acidic, 0~100cm soil bulk density is 1.19g/cm^3, alkaline hydrolyzable nitrogen content is 138.9mg/kg, available phosphorus content is 20.79mg/kg, available potassium content is 179.35mg/kg, organic matter content is 14.3g/kg, pH value is 6.25.

Soybeans in the region are irrigated by sprinkler and drip irrigation. Sprinkler irrigation adopts mobile sprinkler irrigation machinery and equipment and various types of sprinkler irrigator, drip irrigation adopts 1 pipe and 2 rows for arrangement, soybean planting is single ridge planting, its ridge width is 60 cm, plant spacing is 25 cm. The meteorological data used is a series of meteorological data from Heshan Station from 1951 to 2018, which mainly includes environmental information such as minimum and maximum temperature, average relative humidity, wind speed, sunshine, and rainfall in the observation area. The specific data are all from China Meteorological Data Network (http://data.cma.cn/site/index.html).

Model parameters and calculation methods

Calculation of crop water requirements

The water demand of the crop can be obtained by introducing the FAO formula into the crop coefficients of soybeans at different growth stages, and the calculation formula is:

$$ET_C=K_C ET_0 \tag{Eq.1}$$

Formula: ET_C is the water demand of the crop (mm/d). K_C is the coefficient of the crop (dimensionless). ET_0 means the water requirement of the reference crop (mm/d), which is calculated using the Penman-Monteith formula recommended by FAO-56.

Soybean growth period division

The FAO divides the soybean growth cycle into four periods: early growth (Lini), rapid development (Ldev), mid-growth (Lmid) and late growth (Llate). In this study, the whole growth period of soybean was divided into: seeding stage -three-leaf stage (Lini), three-leaf stage-flowering stage (Ldev), flowering stage-podding stage (Lmid), podding stage - drum grain maturity stage (Llate). Crop factors are based on the irrigation series Crop Guidelines for Crop Water Requirements, published by the Food and Agriculture Organization of the United Nations. The four growth periods of soybean and their corresponding KC values are listed in *Table 1*.

Table 1. *Crop coefficient of soybean at different growth stages*

Irrigation mode	Stage parameters	Lini	Ldev	Lmid	Llate
sprinkler irrigation	date	May 10 - June 20	June 21-July 20	July 21-August 10	August 11 - September 20
	Elapsed time/day	40	30	20	40
	KC	0.43	0.63	0.88	0.54
drip irrigation	date	May 15 - June 20	June 21-July 18	July 19-August 15	16 August - 18 September
	Elapsed time/day	35	28	17	33
	KC	0.45	0.60	0.82	0.49

Main soil parameters in the test area

According to the results of field sampling and analysis, the soil parameters were obtained: the 0~100 cm soil layer was mainly black soil, the total effective water volume (TAW) of the root layer was 180 mm/m, the maximum rainfall infiltration rate was 40 mm/d, and the initial soil moisture content was 124 mm/m.

Effective rainfall calculation

The effective rainfall for the model is calculated using the methodology used by the USDA Soil Conservation Service by:

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$$P_e=\begin{cases}[P_d\times(125-0.6\times P_d)]/125 & P_d\leq (250/3)\ mm \\ (125/3)+0.1\times P_d & P_d> (250/3)\ mm\end{cases} \quad \text{(Eq.2)}$$

Formula: Pe is the effective precipitation in October. Pd is the amount of precipitation in October.

Calculation of irrigation water volume

Under drought conditions, the amount of water irrigated to crops during different growing periods is the difference between crop water requirements and effective rainfall, and if the crop water demand is lower than the irrigation amount for a period, the crop does not need to irrigate. The amount of irrigation water during the growth period is the sum of the irrigation water of each growth period, and soybeans are dry land crops, and the calculation formula of irrigation water is as follows:

$$I=Max\ (\sum_{i=1}^{n} ET_C-\sum_{i=1}^{n} P_e,\ 0) \quad \text{(Eq.3)}$$

where, *I* means the amount of supplement that needs to be irrigated. *n* is the time of the reproductive stage (d). ET_C is the water requirement of the crop (mm/d). *Pe* is the effective precipitation (mm/d).

Selection of typical hydrological years

Using the annual rainfall data of Heshan Farm from 1951 to 2018, arranging them in descending order from largest to smallest, and then calculating and fitting the empirical frequency curve through the hydrological empirical frequency formula, different hydrological chronologies can be obtained, and the calculation formula is as follows.

$$P_m=\frac{m}{n+1}\times 100\% \quad \text{(Eq.4)}$$

where: P_m means the empirical frequency value of the mth item of the observation series. *m* indicates the sequence number of the observation series from largest to smallest. *n* is the number of years of the observation series.

According to *Formula (4)*, the rainfall in the local extremely dry year (P=95%) was 291.2 mm, the rainfall in the dry year (P=75%) was 353.6 mm, the rainfall in the normal flow year (P=50%) was 470.3 mm, and the rainfall in the flood year (P=25%) rainfall is 687 mm, and the annual and monthly rainfall at different levels is shown in *Table 2*.

The average monthly rainfall in dry years is calculated as follows.

$$P_{idry}=P_{iav}\times\frac{P_{dry}}{P_{av}} \quad \text{(Eq.5)}$$

Formula: P_{iav} is the average rainfall in the ith month. P_{idry} is the dry annual rainfall in the ith month. P_{av} is the average annual rainfall. P_{idry} is the amount of rainfall in dry years. The calculation formula for the average monthly rainfall in the year of abundant water and the year of peaceful water is the same as above.

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Table 2. *Monthly rainfall of different typical hydrology*

Typical hydrological years	January	February	March	April	May	June	July	August	September	October	November	December
Flood year/mm	6	9.8	12.4	13.9	93.8	109.8	228.1	104.8	51.5	39.1	12.4	5.4
Normal flow year/mm	9.2	10.7	18.2	21.2	32.9	81	56.4	61.4	137.7	15.1	4.3	22.2
Dry year/mm	2	0.6	0	73.4	83.4	45.4	84.3	40.3	12.7	0	6.6	4.9
Extremely dry year/mm	4.6	4.8	12.6	11.2	69.8	62.1	37.3	48.7	7.8	22.9	3.6	5.8
Multi-year average/mm	5.45	6.48	10.80	29.93	69.98	74.58	101.53	63.80	52.43	19.28	6.73	9.58

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Climate propensity rate

Climate tendency rate refers to the rate of change of meteorological factors every 10 years, and a positive climate tendency rate indicates that the corresponding meteorological factors show an increasing trend, and vice versa. This scientific study uses the least squares method to represent the trend of meteorological elements in a linear equation, namely:

$$Y_i = at + b \quad \text{(Eq.6)}$$

Formula: Yi is the fitted value of each meteorological factor. t is the corresponding year. a and b are both regression coefficients.

Mann-Kendall trend test

Mann-Kendall trend test is a kind of non-parametric statistical test, which has a good adaptability to the distribution of non-normal data and can well analyze the time series between weather data, so as to reflect the change trend of meteorological factors. The positive and negative values of the statistical variable Z indicate that the data change is increasing or decreasing. When the absolute value of Z is greater than or equal to 1.28, the significance test with 90% confidence, the significance test with 95% confidence at 1.64, the significance test with 99% confidence at 2.32 and the significance test with 99.9% confidence at 2.56. Mann-Kendall mutation test is to calculate two statistics of UFK and UBK and draw a graph of the two variables. Finally, it is analyzed, and its changing trend and mutation point are obtained.

Coupling of crop water requirements to effective rainfall

During the growing period of the crop, the degree of satisfaction between effective rainfall and crop water demand is called the coupling degree between crop water demand and effective rainfall, and its calculation formula is as follows:

$$\lambda_i = \begin{cases} 1 & (P_i \geq ET_{Ci}) \\ P/T_{Ci} & (P_i < ET_{Ci}) \end{cases} \quad \text{(Eq.7)}$$

where: is the coupling degree of the i-th period. $P\lambda_{ii}$ represents the effective rainfall in the ith period (mm). ET_{ci} is the water requirement of the crop in the ith time period (mm).

Results and analysis

Trend analysis of meteorological factors

From the trend of meteorological factors in each growth period of soybean (see *Table 3*), it can be seen that the change trend of average minimum and maximum temperature, relative humidity and rainfall increases first and then decreases, and the change trend of average wind speed and sunshine time decreases first and then increases. The average temperature of each month during the growth period of soybean increased significantly, and the added value increased at a rate of 0.36, 0.52, 0.22, 0.30 and 0.37°C/10 years, respectively. The average relative humidity decreased slightly in all months except May. The average wind speed during the growth period was decreasing, decreasing at rates of 0.56, 0.40, 0.43, 0.35 and 0.53 (m/s)/10 years, respectively, and all passed the significance level test of 0.001; the rainfall in May, June and September

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showed an increasing trend, and the rainfall in July and August showed a decreasing trend. Among them, the rainfall in July decreased the fastest at a rate of 5.46 mm/ 10 years.

Table 3. *Trend analysis of meteorological factors in soybean growth period*

Month	Project	Average temperature/°C	Average humidity/%	Average wind speed/m.s-1	Hours of sunshine/h	Rainfall/mm
May (L_{ini})	average value Z value Climate propensity rate	14.87 2.62*** 0.36	50.28 1.26* 0.66	4.40 -6.45*** -0.56	242.84 -2.62*** -9.76	38.52 0.88 3.63
June (Lini)	average value Z value Climate propensity rate	20.60 3.96*** 0.52	60.54 -0.11 -0.42	3.48 -6.43*** -0.40	248.32 -2.06* -7.45	76.05 0.72 3.95
July (Ldev)	average value Z value Climate propensity rate	23.14 2.53*** 0.22	72.28 -0.86 -0.36	3.29 -5.82*** -0.43	230.35 -2.44*** -9.04	136.78 -1.31* -5.46
August (Lmid)	average value Z value Climate propensity rate	21.54 3.11*** 0.30	74.55 -1.72* -0.61	2.90 -5.20*** -0.35	228.61 -1.14 -3.70	110.22 -0.24 -1.04
September (Llate)	average value Z value Climate propensity rate	6.38 2.93*** 0.37	60.85 -0.90 -0.58	3.62 -6.52 -0.53***	239.55 -2.04* -5.49	22.78 0.71 0.32
Reproductive period	average value Z value Climate propensity rate	17.31 3.03*** 0.35	63.70 -0.47 -0.26	3.54 -6.08*** -0.45	1189.67 -2.06** -7.09	384.35 0.15 0.28

Note: *, ** and **** indicate significant at the levels of 0.05, 0.01 and 0.001, respectively

Analysis of soybean water demand, effective rainfall, and irrigation water demand

The monthly variation trends of soybean growth water demand, effective rainfall, and irrigation water demand during the growth period from 1951 to 2018 are shown in *Table 4*. The water demand of soybean decreased at a rate of 9.15 mm/10 years during the growth period, the range of change was 300.29~ 526.14 mm, and the average value was 413.17 mm. The variation range of water demand in each month was large, among which the maximum variation range of soybean water demand in July was 66.50 mm, and the climate tendency rate was 2.83 mm/10 years. The effective rainfall during the growth period showed a downward trend, and the range of change was 59.66~ 553.84 mm.

The monthly effective precipitation of soybeans at different growth periods showed a trend of first increasing and then decreasing. Among them, the effective rainfall in May increased at a rate of 3.06 mm/10 years in the early stage of soybean growth and decreased at a rate of 3.28 mm/10 years in September, which is likely to lead to drought in the late growth period of soybeans. The variation range of irrigation water demand was between 20.72~433.59 mm and decreased at a rate of 7.90 mm/10 years. The average irrigation water demand of soybeans during the whole growth period was 227.16 mm, and the

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minimum irrigation water demand in each month of the soybean growth period was 0 mm except August, indicating that August was the key period for soybean growth.

Table 4. *Variation trend of soybean water demand, effective rainfall, and irrigation water demand*

Month	Project	Crops require water	Effective rainfall	Water requirements for irrigation
May	Variation range/mm	35.20～69.00	0～70.24	0～59.48
	Average/mm	52.10	35.12	29.74
	Z value	-3.38***	1.23***	-2.04***
	Climate propensity rate	-1.84	3.06	-2.51
June	Variation range/mm	58.30～104.80	9.20～120.70	0～90.55
	Average/mm	81.55	64.95	45.28
	Z value	-2.24***	1.66*	-1.96*
	Climate propensity rate	-1.90	3.71	-3.63
July	Variation range/mm	88.30～154.80	42.26～124.80	0～104.38
	Average/mm	121.55	83.53	52.19
	Z value	-2.54**	-0.84	1.10
	Climate propensity rate	-2.83	-2.01	1.45
August	Variation range/mm	80.03～125.24	6.0～145.80	20.72～114.38
	Average/mm	102.64	75.9	67.55
	Z value	-1.62*	-0.73	-1.44*
	Climate propensity rate	-1.51	-1.93	-1.38
September	Variation range/mm	38.46～72.30	2.2～92.30	0～64.80
	Average/mm	55.33	47.25	32.40
	Z value	-2.11*	-2.36*	-1.54**
	Climate propensity rate	-1.07	-3.28	-1.83
During the reproductive period	Variation range/mm	300.29～526.14	59.66～553.84	20.72～433.59
	Average/mm	413.17	306.75	227.16
	Z value	-2.38*	-0.21	-1.18
	Climate propensity rate	-9.15	-0.45	-7.90

Correlation analysis between soybean water demand and meteorological factors

Based on the correlation analysis of the water demand, effective rainfall, and irrigation water demand of local soybeans during the whole growing period and the meteorological elements in the region (see *Table 5*), it can be seen that crop water demand and irrigation water demand are positively correlated with the average temperature, average wind speed and cumulative sunshine duration, and negatively correlated with the average relative humidity and cumulative rainfall. Effective rainfall was positively correlated with average relative humidity and cumulative rainfall, but negatively correlated with average temperature, average wind speed and cumulative sunshine duration, and weakly correlated with average temperature and average wind speed.

The local meteorological factors have great influence on the water requirement of soybean, among which the temperature and wind speed have significant influence on the transpiration and evaporation of crops. It can be seen from *Table 3* that the average temperature increased at a rate of 3.03℃/10 years and the average wind speed decreased at a rate of 0.26 (m/s) /10 years during the soybean growth period. The combined effect

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of these two factors has significantly changed the water requirements of crops. This is mainly because rising temperatures will accelerate the evaporation of crops. The decrease of wind speed will reduce the rate of air flow in the field, which will reduce the evaporation ability of crops. It can be seen from *Table 4* that the correlation between soybean water demand and average temperature is lower than that between soybean water demand and average wind speed.

Table 5. *Correlation analysis between water requirement of soybean and meteorological factors in growth period*

Project	**Average temperature/°C**	**Average humidity/%**	**Average wind speed/m.s-1**	**Cumulative sunshine hours/h**	**Cumulative rainfall/mm**
Crops require water	0.189	-0.464	0.447***	0.783**	-0.411**
Effective rainfall	-0.138	0.482	-0.126	-0.241	0.838**
Water requirements for irrigation	0.082	-0.505**	0.376**	0.563**	-0.722**

Water requirements of soybeans of different hydrological years

In this study, 2007, 2005, 1955 and 2013 were selected as the representative years of the regional extremely dry year, dry year, normal flow year and abundant water year of the Agricultural Reclamation Ninth Third Management Bureau, and the typical hydrological year was calculated based on the rainfall data of many years, and the calculation results are shown in *Figure 1*. The water demand of soybeans in each hydrological year showed a trend of first increasing and then decreasing. The water requirements of soybeans in the whole growth period of abundant year, normal flow year, dry year and extremely dry year were 396.06, 390.65, 420.21 and 459.96 mm, respectively. In the whole growth period of soybean, there is little difference in water demand in the seedling stage, three-leaf stage and drum grain maturity stage, and the flowering stage and podding stage are very different. Among them, from seeds to germination accounts for about 9.7% ~ 11.4% of the total water demand, seedling to branch accounts for about 19.6% ~ 23.3% of the total water demand, branching, flowering, and podding stage. The demand for water continues to increase, accounting for more than 48.55~54.62% of the total water demand, the podding stage to the drum stage accounts for about 22.7% ~ 26.4% of the total water demand, the temperature from the drum grain to the ripening stage gradually decreases, the soybean leaves gradually fall off, and the water demand of crops at this stage decreases, accounting for 8.5%～ 12.4% of the total water demand. Experimental calculations show that soybean accounts for the largest proportion of water demand in flowering and podding stage, and the difference in water demand in different hydrological years is mainly caused by the difference in water demand in the flowering stage and podding stage.

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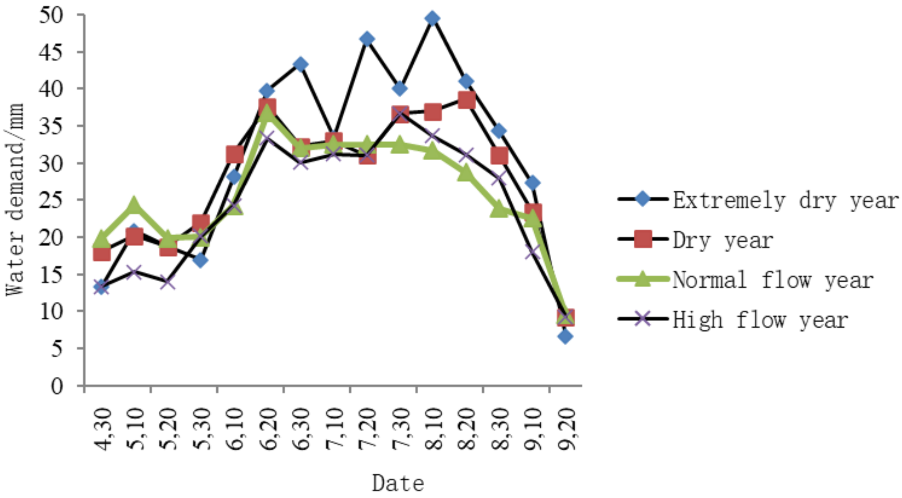

Figure 1. *Water demand of soybean in different hydrological years*

Analysis of coupling degree of water demand and effective rainfall of soybean in different hydrological years

The water requirements, effective rainfall and coupling of crops in four typical years are shown in *Figure 2*. According to the figure, the trend of effective rainfall is first rising and then decreasing. Among them, the effective rainfall was the lowest in May, and the peak effective rainfall was abundant in July, indicating that there was a lack of rainfall at the seedling and branching stages, and abundant rainfall at the flowering and podding stages. In the year of abundant water, the year of flat water has abundant rainfall, and the coupling degree of water demand and effective precipitation of soybeans in each month is above 1. The above analysis shows that the precipitation of the two typical years can better meet the water demand requirements of soybeans. In dry years, the coupling degree is greater than 1 only in September.

The remaining months were less than 1, indicating that the soybeans only needed water during the ripening period to meet the growth demands. The coupling degree of each month of the extremely dry year was less than 1, indicating that the rainfall at each growth stage could not meet the water demand of soybean during the entire growth period. The coupling degree analysis showed that the coupling degree was lowest in July and August (flowering stage and podding stage) in dry year and extremely dry year, indicating that soybeans in this growth stage were severely short of water. Therefore, priority scientific supplementary irrigation schemes for these two growth stages are needed based on the full use of local precipitation, so that the water demands of soybeans can be met at the critical stage of fertility.

Determination of soybean irrigation system

When spraying irrigation is used, the simulated depth of wet layer is 0.3 m in the early growth period, and 0.6 m in the middle and late growth period. According to the provisions of "Technical Specifications for Sprinkler Irrigation Engineering (GB/T 50085-2007)", the water utilization coefficient of the pipeline system is 0.95. Combined with the average wind speed during the soybean growth period in *Table 3*, the field spraying water utilization coefficient is 0.87, so the field spraying irrigation water utilization coefficient is 0.83. When drip irrigation is used, the simulated depth of wet

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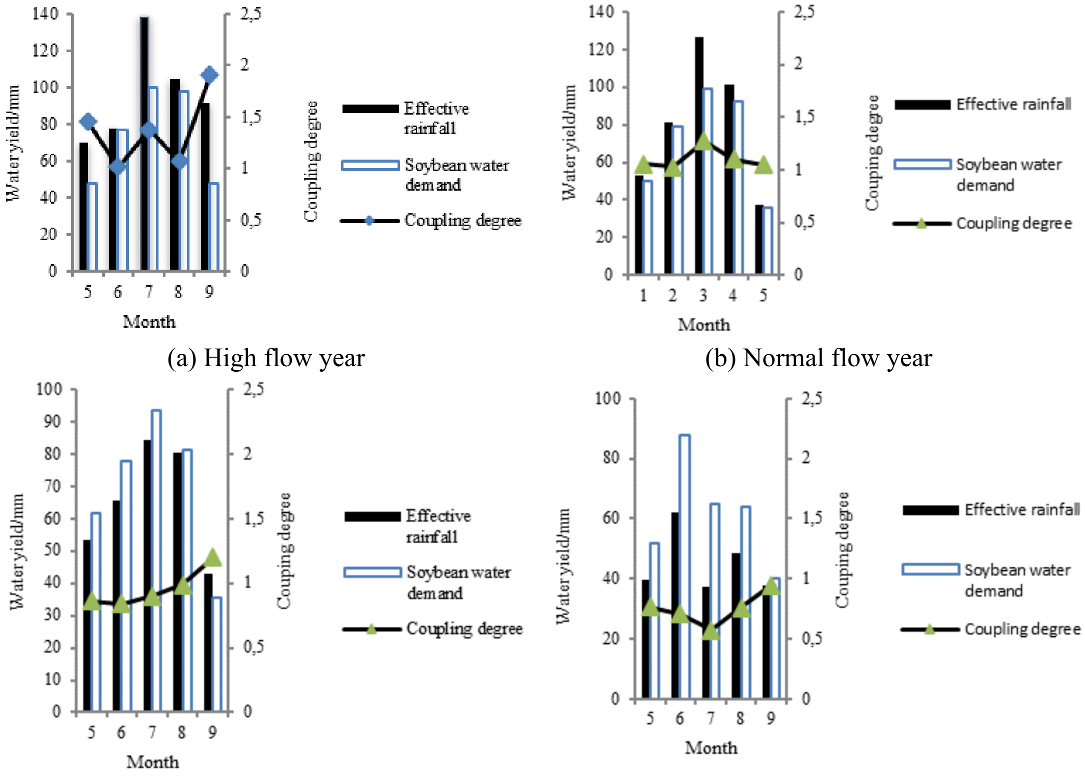
layer is 0.3 m in the early growth period, and 0.5 m in the middle and late growth period. The moisture ratio of soil layer is 65%, and the utilization coefficient of irrigation water is 0.95. Considering that the optimal moisture content suitable for soybean growth is 0.60~ 0.85 of field water retention (Shi et al., 2006). Therefore, when the soil moisture content is less than 60% of the field water holding rate, it is necessary to carry out supplementary irrigation to 85% of the upper field water holding rate.



(a) High flow year (b) Normal flow year

(c) Dry year (d) Extremely dry year

Figure 2. *Coupling degree of soybean water demand and effective rainfall in different hydrological years*

CROPWAT was used to simulate the irrigation system of soybeans, and the results were shown in *Table 6*. In wet years, the water requirements of soybeans can be met, so there is no need for irrigation. Under the condition of sprinkler irrigation, the irrigation quota of normal, low, and extremely low water years was 68.4, 121.1 and 175.9 mm, respectively. Irrigation frequency is 1 time in normal year, 3 times in dry year and 4 times in extremely dry year. Under drip irrigation conditions, the irrigation quota in normal year, low year and extra low year was 66.3, 111.6 and 151.5 mm, respectively. The irrigation frequency was 2 times in normal year, 3 times in dry year and 4 times in extra low year. The difference of irrigation system under different irrigation methods is mainly caused by the different utilization coefficient of irrigation water, the length of corresponding growing stage of crops, the planned wetting layer, and the ratio of irrigation wetting.

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Table 6. *Irrigation schedule of sprinkler and drip irrigation for soybean in different hydrological years*

Annual pattern of rainfall	Sprinkler irrigation		Drip irrigation	
	Date of irrigation	Irrigation quota/mm	Date of irrigation	Irrigation quota/mm
Normal flow Year	8.19	68.4	5.21	26.8
	-		7.17	39.5
total		68.4		66.3
Dry years	5.25	40.8	5.30	34.3
	7.20	45.0	6.16	35.6
	8.17	35.3	8.24	41.7
total		121.1		111.6
Extremely dry year	5.26	51.2	5.28	34.9
	6.19	45.5	7.10	44.8
	7.4	38.6	8.6	39.4
	8.2	40.6	8.18	32.4
total		175.9		151.5

Discussion

Many scholars have used the CROPWAT model to perform numerical simulations of water requirements and irrigation systems of different crops (Xu et al., 2015; Guo et al., 2016). They also agree that irrigation should be started when the water content of the crop is consumed to the lower limit of the field water holding rate, until the water content of the crop reaches the field water holding rate. However, this kind of irrigation method is only considered from the perspective of water consumption during the whole growth period of crops, and does not really consider the best requirements for soil moisture content of crops at different growth periods, which will cause crops to absorb excessive water, thereby affecting the respiration of crop roots, and then causing crop lodging and yield reduction; It also affects the use of rainfall by crops. When the soil moisture content is too high after reirrigation, rainwater will lead to partial leakage of soil moisture and runoff loss. In addition, none of the above studies involved the study of crop water requirements and irrigation systems corresponding to different irrigation methods. In this study, the suitable soil moisture content of crops at different growth stages was considered comprehensively, and the water requirement and irrigation system of soybeans were calculated and simulated by two different irrigation methods, namely sprinkling irrigation, and drip irrigation. At the same time, the double changes of climate and KC in each growth period of soybean were considered and corrected, which made the simulation method more consistent with the actual growth state and the experimental results more accurate.

The average wind speed and low rainfall in spring in the western part of Heilongjiang Province lead to low soil moisture content, which has a certain impact on crop seed germination. Therefore, an appropriate amount of irrigation should be carried out during spring sowing to ensure the survival rate of seedlings. The key period for soybean growth is the flowering period, during which the most water demand is required, and if sufficient water is not guaranteed at this time, it will cause serious yield reduction. Therefore, to ensure the supply of water during this period, the relative moisture content of the soil should be kept at 70%~80% of the water holding capacity in the field. In the extremely dry year and dry year, in order to ensure the normal physiological growth of crops and

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the amount of water required for production, appropriate irrigation should be carried out at the branching stage and podding stage.

Conclusion

This study analyzes the trends and correlations of meteorological factors, soybean water demand and effective rainfall between 1951 and 2018 of the Jiusan Management Bureau of Reclamation District of Heilongjiang Province, summarizes the changes of local meteorological factors in different periods, and discusses the reasons for the changes in soybean growth demand and irrigation water demand in different periods. By comparing and analyzing the changes of water demand, effective rainfall and coupling degree of soybean under different hydrological age patterns, an irrigation system suitable for local soybean growth and development under different hydrological age patterns was established. This study not only provides a theoretical basis and technical support for improving the efficiency of agricultural water resources in the local soybean production process, but also provides an effective reference for the implementation of the national crop irrigation program.

(1) During the soybean growing period, the meteorological factors of each month have obvious changes, which are manifested as rising temperature, decreasing wind speed, and decreasing rainfall. During the growing period, the water demand of soybeans decreased at a rate of 9.15 mm/10 years, effective rainfall increased at a rate of 3.06 mm/10 years in May, decreased at a rate of 3.28 mm/10 years in September, and decreased at a rate of 7.90 mm/10 years in irrigation.

(2) The water demand of soybeans in this region was quite different in different hydrological years, with the annual water demand of 396.06 mm for abundant water, 390.65 mm for flat water, 420.21 mm for dry water, and 459.96 mm for very dry year. However, the difference between flowering and podding stage is the greatest.

(3) The coupling degree of effective rainfall and soybean water demand under different hydrological age patterns increased first and then decreased. The coupling degree between crop water demand and effective rainfall in each month of the abundant year and the water year was greater than 1, indicating that the effective rainfall of these two hydrological years could meet the water demand of soybean. In dry years, the coupling degree is greater than 1 only in September, and the rest of the months are less than 1, indicating that only the moisture of soybeans in the mature period can meet the demand. The coupling degree of each month of the extremely dry year was less than 1, indicating that the rainfall in each growth period could not meet the water demand of soybean during the entire growing period.

(4) The simulation results of the soybean irrigation system by CROPWAT showed that under the sprinkler irrigation conditions, the irrigation quotas in the normal flow year, dry year and extremely dry year were 68.4, 121.1 and 175.9 mm, respectively. The irrigation frequency was 1, 3 and 4 times, respectively. Under drip irrigation, the irrigation quotas in normal flow year, dry year and extremely dry year were 66.3, 111.6 and 151.5 mm, respectively. The irrigation frequency was 2, 3 and 4 times, respectively. In order to ensure high and stable soybean yield, priority should be given to ensuring sufficient water supply during the flowering and podding stages of soybeans. Therefore, in different hydrological years, proper irrigation should be carried out at the flowering and poddingding stages of soybean to ensure high and stable yield of soybean.

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