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Optimal Irrigation Scheduling for Summer Maize Crop: Based on GIS and CROPWAT Application in Hetao District; Inner Mongolia Autonomous Region, China

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Abstract

Net Irrigation Water Requirement was estimated using GIS and CROPWAT software. The study aims to develop an optimal irrigation scheduling in summer, to increase crop yield under water scarcity conditions. The proportion of rainwater evaporated over year 2008 "868.6 mm/dec" was used to compare with the water requirements of the maize crop "734.1 mm/dec" The results showed deficits ranging between 30.7 mm/month and 200.8 mm/month, for the period between April and September. In addition, there was uneven distribution of precipitation and an irregular basis during the agricultural year (2000-2008). The ET_0 was between 0.47mm and 3.08mm, and net irrigation water requirement was 833.4 mm for the maize crop. On refilling soil to field capacity with irrigation at critical depletion, 70% field efficiency was achieved which correspond to optimal condition, while adapting fixed interval per stage gave a yield reduction of about 2.5 %.

Keywords: Evapotranspiration; ArcGIS; CROPWAT; Optimal Irrigation Scheduling; Corn

1. Introduction

Development in Hetao Region, like many regions in developing countries, is based on Agriculture. Currently, roughly 70 % of freshwater withdrawals are used for agricultural production (FAO, 2005; Xiong et al., 2010; Fader et al., 2011); particularly, in China where the proportion is more than 60% (MWR, 2010). Irrigation's water use is the major part of agricultural water consumption in China, which accounts for nearly 90% of total agricultural water use. Meanwhile more than three-quarters of the grain production come from irrigated areas that make up 48 % of the total cultivated land of China (MWR, 2005). Therefore, the inadequacy of many existing irrigation systems is the main obstacle to the development of water use efficiency in agriculture. Irrigation technologies and irrigation scheduling may be adapted for more effective and rational uses of limited water supplies.

Surface irrigation or gravity fed by channels, practiced in the Hetao Irrigation District suffers from high evaporation and does not target plants. The poor applications of water saving practices and the increase of the groundwater abstraction have caused a decline of groundwater table in Hetao Irrigation District. The surface irrigation techniques result in an excessive intake of water. The flood irrigation leads to use of more than 90% of diverted water to produce crops. Annual average water diversion from the Yellow River is 5.165 billion m^3 (from 1980 to 2000), which account for about 1/10 of average annual river discharge of (53.5 billion m^3 measured at Huayuankou station from 1956 to 2000). However due to the impacts of human activities and climate change, runoff within the Yellow River basin has decline significantly during the past fifty years (Fu et al., 2004; 2007). The global and regional projections showed warming trends are likely to continue in the region during the 21st century (Houghton et al., 2001; Nijssen et al., 2001) which will further decrease runoff and exacerbate water resource shortage in the basin. Water is lost through several ways, one of them is evapotranspiration. Evapotranspiration (ET) is the most active process in the hydrological cycle and a major component of energy and water balance in agriculture ecosystems (Oki and Kanae, 2006; Burba and Verma, 2005). The alternative way to solve this problem is to develop an optimal irrigation scheduling. Water shortage is a problem to which a solution is needed urgently to make agricultural irrigation fit to the limited water allocation. Doing so will guarantee agricultural sustainable development in the Hetao Irrigation Area. In a context of increasing scarcity, information should be a key element in the search for effective water management, particularly in the irrigation fields. Since the implementation of its reform and open up policy in the late 1970s, China has achieved great economic success at a rapid and stable pace (Xia and Yongqing, 2010), meanwhile experienced enormous social transformation. As one of the largest developing country, China has a vast area of 9.6 million km^2 and relatively abundant natural resources. One of the most precious natural resources is the Yellow river, which is a source of irrigation water in Hetao Irrigation Disrict. The water is utilized for irrigation, public water supply, livestock, and industrial purposes. Hetao District is one of the most important food production bases in Northwest China, producing 35% of sunflower, 37% of wheat and 36% of sugar beet of Inner Mongolia autonomous region (Wang et al., 1993; IWC-IM, 1999). About 5.2 billion m^3 of water are diverted each year from the Yellow river to irrigate this area (IWC-IM 1999; Hetao administration, 2003).

Due to the dominance of the monsoon climate, the temporal and spatial distributions of water resources are highly uneven. Poor irrigation and drainage management practices in Hetao irrigation District have caused severe water logging and salinity in the upstream irrigation Districts (Wang et al., 1993; Fang and Chen 2001). The present study used Geographic Information System (GIS) for spatial analyses and CROPWAT software to develop irrigation schedule based on the time to irrigate and the amount of water required. To accomplish the indicated purpose the following objectives were set: (1) to estimate monthly evapotranspiration during corn growing season from climatic data using CROPWAT model version 8.0; (2) to determine effective rainfall using USDA SCS method; (3) to determine crop water requirement and develop an optimal irrigation scheduling in the Hanghou Irrigation Districts; (4) to analyse and compare the model's results between optimal schedule treatments and stress water treatments in the Hanghou Irrigation Districts.

2. Study area

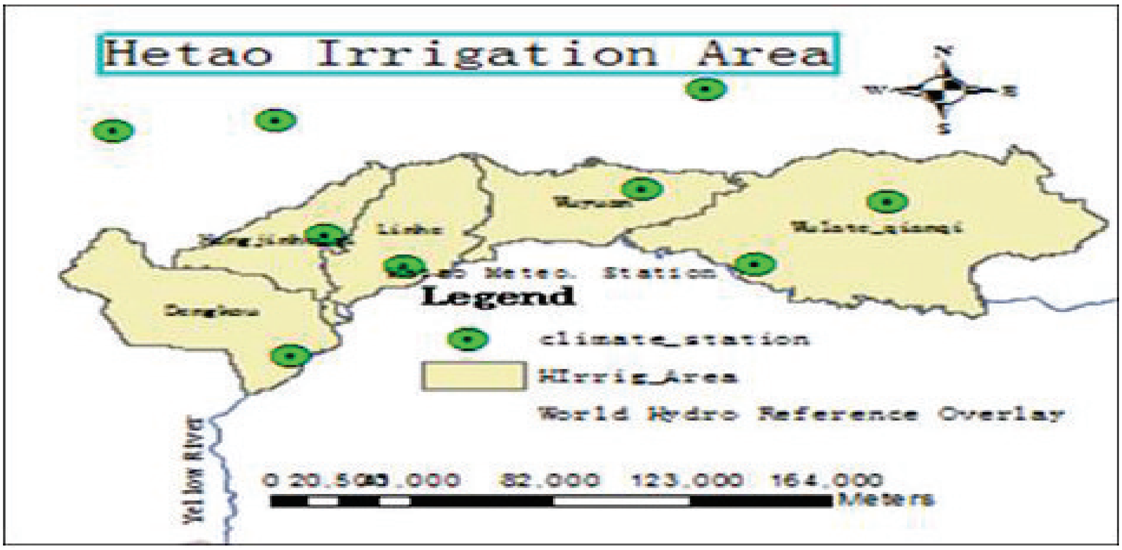


Figure 1 Hetao irrigation area

The Hetao Irrigation District is located (N 40.1°- 41.4°E 106.1°-109.4°) in the western part of Inner Mongolia Autonomous Region, North China. Five counties in the district with the largest water diversions were selected for this study (Figure 1). The area is characterized with a typical continental climate, being very cold in winter with little snowfall and very dry in summer. Average annual temperature is about 5.6 -7.4°C. Most parts of the study area is plain with the elevation slightly higher in the south-west and lower in the northeast (a.s.l. 1028 - 1062 m), except for a mountain region in the north-west of Dengkou County (a.s.l. 1059 - 2012 m). Besides, in the central and southern part of Dengkou County, there is an extensive area of sandy land and Gobi desert. The groundwater ranges from 0.8 to 2.6 m annually, and the soil texture is silt-clay loam with salinity (Yu et al., 2010). About 75% of the Hetao Irrigation District has mild to moderate soil salinity and 25% has severe soil salinization. Hetao is one of the three largest irrigation Districts in China. Covering an area of 1.12 M_{ha}, whose major part (570,000 ha) is irrigated land. In the Shahaoqu Experimental Station soil texture, salinity, and groundwater were considered as a representative of the region's hydrogeology. The site receives 136 mm precipitation annually and potential evaporation is 1938 mm. The average number of sunlight hours per month is 266h. Cumulative annual solar radiation is about 6000 MJ m^{-2}. Soils begin freezing in the second half of November and freezes to a depth of about 1.0 - 1.3 m, and completely thaw in the middle of May. The duration of freezing-thawing is about 180 days. Spring wheat, summer maize and sunflower are predominant crops in the Irrigation district. The growing season for spring wheat is from late March to mid-July, while maize and sunflower are planted in late April, late May and harvested in mid-September and mid-October, respectively.

3. Maize Crop

Maize is an important staple food in developing countries, particularly, in Latin America, Africa, and Asia. It is a basic ingredient for food products and local drinks. In addition, it is used as feed for livestock, high in energy, low in fibre and easily digestible. As a source of starch, it is a major ingredient in industrialized food products. Maize is 2~3 m high grass with a solid single stern (stalk), 3~4 cm in diameter, with clearly defined nodes and inter-nodes. For early planting, sow seed only 2.5 cm deep; in the hot weather of mid-summer, plant up to 5.1 cm deep. The average germination rate for sweet corn is about 75%. They germinate within seven to 10 days. Proper farm management practices should be carried out to ensure proper production and good yield. Weed control and gapping in case of unwanted seedlings. During weeding care should be taken to avoid disturbing the roots. For early planting, corn need about 2.5 cm of water a week, particularly when the stalks begin to tassel. Water stress during pollination will result in ears with lots of missing kernels, so a farmer should not skip watering the corn path. Apply water at the soil surface by using a soaker hose or drip irrigation and avoid spraying plant from above, which could wash pollen off the flowering tops. Maize appears relatively tolerant to water deficits during the vegetative and ripening periods. Greatest decrease in grain yields is caused by water deficits during the flowering period. The effect of limited water on maize grain yield is considerable and careful control of frequency and depth of irrigation is required to optimize yield under conditions of water shortage. When evaporative conditions correspond to ET_c of 5 to 6 mm/day, soil water depletion up to about 55% of available soil water has small effect on yield (p = 0.55). To enhance rapid and deep root growth a somewhat greater depletion during early growth periods can be advantageous. Depletion of 80% or more may be allowed during the late season. Where rainfall is low and irrigation water supply is restricted, irrigation scheduling should be based on avoiding water deficit during the flowering period, followed by yield formation period.

4. Materials and Methods

Field data from Hetao research project (HRP) were used to estimate reference evapotranspiration using CROPWAT model. The reference evapotranspiration was used to simulate optimal irrigation schedule. In the field studies, various irrigation treatments were applied to maize crops. In addition, water stress at each growth stage, and soil moisture status were determined over the growing season. The reported information on climate, soil and crop constituted the input data, while the study used reported yield and crop consumptive water to validate the various crop parameters in CROPWAT model. CROPWAT 8.0 is a computer program for calculating crop water requirements and irrigation requirements based on soil, climate and crop data. In addition, the program allows development of irrigation schedules for different management conditions and calculation of scheme water supply for varying crop patterns. It can also be used to evaluate farmer's irrigation practices and estimate crop performance under both rain-fed and irrigated conditions. All calculation procedures used in CROPWAT 8.0 are based on two FAO publications of irrigation and drainage series, namely, No. 56 "crop evapotranspiration-Guidelines for computing crop water requirements"(1998) and No. 33 titled "Yield response to water requirements" (1979). Once all the data were entered, CROPWAT 8.0 windows automatically calculates and displays results in a table form or graphic form.

Table 1: CROPWAT Model input parameters and the output results

Data	Input	Output
	Et_o calculated with	Crop Water Requirements
Climate	Penman Monteith	Irrigation Requirements
	Rainfall Data	
	Kc, crop description,	
Crop	Maximum. rooting depth,	Actual crop
	% Area covered by plants	Evapotranspiration
	Initial soil moisture	Daily Soil Moisture Deficit
soil	condition and Available	Irrigation Scheduling
	Soil moisture	
	Irrigation Scheduling	Estimation Yield Reduction
Irrigation	Criteria	due to crop stress

Table 2: Corn Crop data

Dry crop Data (File: Hh-corn.CRP)					
Crop Name: corn		Planting Date: 21/04			Harvest: 17/09
Stage	initial	Dev.	Mid.	Late	Total
Length (days)	30	50	50	20	150
Kc values	1.15		1.25	0.35	
Rooting depth (m)	0.3		1.2	1.2	
Critical depletion (p)	0.55		0.55	0.80	
Yield response (f)	0.4	0.8	0.6	0.25	1.25
Crop height (m)			2		
CROPWAT 8.0					

The CROPWAT model operates in two modes, namely computing the evapotranspiration using climatic parameters and using direct field evapotranspiration measurement values. In this study evapotranspiration was computed using climatic parameters. The results are useful for comparison of optimal treatments and stress treatment of irrigation. Water requirements were calculated according to the cropping pattern provided in the programs. The evapotranspiration (ET_0) was computed by Penman-Monteith Model, which is based on the FAO guidelines No. 56 of the irrigation and drainage series “crop evapotranspiration-guidelines for computing crop water requirement” (FAO, 1998). FAO-56 PM ET_0 equation by Allen et al. (1998), is given in equation (1):

$$ET_0 = \frac{0.408\Delta(R_n - G)\gamma\left(\frac{900}{T+273}\right)U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

Where: ET_0 = the grass reference evapotranspiration (mm/day); R_n = the net radiation at the crop surface (MJ/m); e_s = the saturation vapor pressure (kPa); e_a = the actual vapor pressure (kPa);

e_s - e_a = the saturation vapor pressure deficit (kPa); Δ = the slope vapor pressure curve (kPa/oC); and γ = the psychometric constant (kPa/oC).

The crop water requirements (CWR) are calculated taking into consideration the evapotranspiration rate. This depends on climatic conditions, growing season and crop development stage (FAO, 1977). Crop evapotranspiration under standard condition (ET_c) is the sum of transpiration by the crop and evaporation from the soil surface. At sowing nearly 100% of ET comes from evaporation, while at full crop cover more than 90% of ET comes from transpiration. CROWPAT Software is based on a few variables. All these variable turn around the water balance (F. Langlois, 2006) written in the following general form:

$$R_i = R_{i-1} + R_{ef} + I_{rr} - D - ET_m \quad (2)$$

Where: R_i = soil water content per day (mm); R_{i-1}= soil water content in the day i-1 (mm); R_{eff} = P_{eff} = effective precipitation (mm); I_{rr} = contribution of irrigation (mm); D = drainage;

CWR= crop water requirement, represent maximal evapotranspiration (ET_m).

This equation includes all essential variables for software application. First, effective rainfall; which correspond in agriculture, the rain water part which contributes to replenish the reserve of the soil water usable by crop. They take into account the values of total precipitation and runoff. The program uses the Penman-Monteith formula (5). After ET estimation, using Penman-Monteith the effective rainfall was calculated with the following formula based on monthly rainfall, USDA-SCS method.

$$P_{eff} = \frac{P_i(125 - 02P_i)}{125} \quad (3)$$

Or when rainfall is below 250 mm, effective precipitation (mm) is calculated using equation

$$P_{eff} = 125 - 0.1P_i \quad (4)$$

Where: P_{eff} = effective precipitation (mm); P_i = soil water content per day (mm).

The following equation is a water production function and can be applied to all agricultural crops, i.e. herbaceous, trees.

$$1 = \frac{Y_a}{Y_m} = K_y\left(1 - \frac{ET_a}{ET_m}\right) \quad (5)$$

Where Y_m and Y_a are the maximum and actual yields, ET_m and ET_a are the maximum and actual evapotranspiration. The response factor performance (K_y), is a yield response factor representing the effect of a reduction in evapotranspiration on yield losses.

The allowable depletion (P) represents the critical level of the reserve from which stress due to lack of water is felt, and the crop height.

5. Results and Discussion

5.1 Evaporation

The data for annual evaporation in Hanghou in 2008 ranged between 48.8 mm in December and 406 mm in (February. The latitude and longitude are N 40.15 and E 107.88 and the values from January through December are the average monthly evaporation recorded during the period at this location, ranging from 0.47 mm to 3.08 mm, whose annual total is 2631.3 mm. The evaporation data were obtained from Hetao Water Development Board as shown In Figure 1. Except the lower values of Hanghou, there was a general tendency for lower evaporation values of Qiangqi to the East and higher values to the Wuyuan, Linhe and Dengkou to the West, annual evaporation of all the stations plotted against the longitude of the station. Except Hanghou, there was a general trend of the evaporation increase from East to West of Hetao. Opposite that Figure, the same kind of graph for Evaporation and latitude is created, and there is not tendency for evaporation to vary with latitude like the longitude case.

All meteorological data were obtained from agro meteorological station in Hetao. CROPWAT was used to calculate the average monthly reference evapotranspiration (ET_0) values using the Penman-Monteith method. The ET_0 during the study year (2008) was between 0.47 mm/day to 0.92 mm/day in January to April and 5.73 mm/day to 5.47mm/day during the months of May to July. The crop factor Kc (Table 2) is influenced by irrigation methods and production practices such as irrigation intervals, ground cover at full growth stage and the wetted area. Development of CROPWAT illustrates the variation of crop factor for the corn during the growing period from late April to September.

Total monthly rainfall and effective rainfalls during the growth period of corn in this study area was obtained from CROPWAT database for Hanghou station. Monthly effective rainfall varied between 1.4 mm to 58.1 mm, with peak rainfall during the month of July. The effective rainfall was 150.3mm calculated using CROPWAT reference evapotranspiration which is far less than crop water requirements (734.1,). In addition, the reliability and the distribution of the effective rainfall in the study area is not guaranteed. This is a clear evidence for the need to irrigate for sustainable agriculture. Crop water requirements are affected by rainfall, temperature, humidity, wind speed and radiation. A high intensity of irradiation results in a high rate of water evaporation from soil and plant surface. Table 3, shows application to 100 % of field capacity with irrigation at 100 % depletion achieved 70 % of *field efficiency* where yield reduction was “zero”. These met conditions and data for the optimal irrigation treatment (with no stress water applied). Second step with water stress consisted of application to 100 % of field capacity with Irrigation at fixed interval per stage), where the yield reduction was 2.5 %. This was achieved by adapting fixed interval per stage (Interval in days: initial 7, development 7, mid 20, late 7.

5.2 *Water supply*

The deficits is provided for Maize crop (Table 4). The *net irrigation requirements* expressed in mm/month: 53.2 (April), 200.8 (May), 190.2 (Jun), 150.5 (July), 108.6 (August), 30.7 (September). Net irrigation requirements are a weighting by percentage of surface of the deficits of each crop. The adopted date of plantation was 21/04 while the dates of harvest were automatically calculated according to the total duration of the crop specified on the level of the crop duration stages (17/09). Also specify the percentage of surface occupation, not to be exceeded 100%.

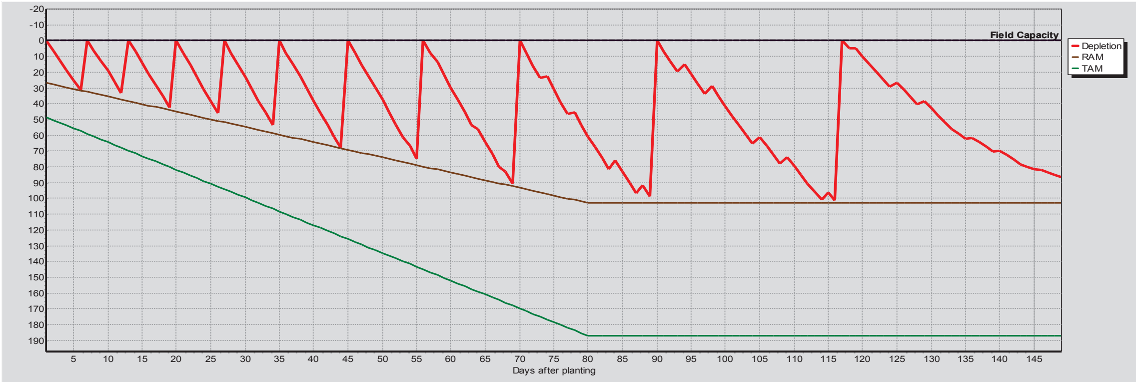


Figure 2: optimal irrigation scheduling (with no water stress applied) example of 2008

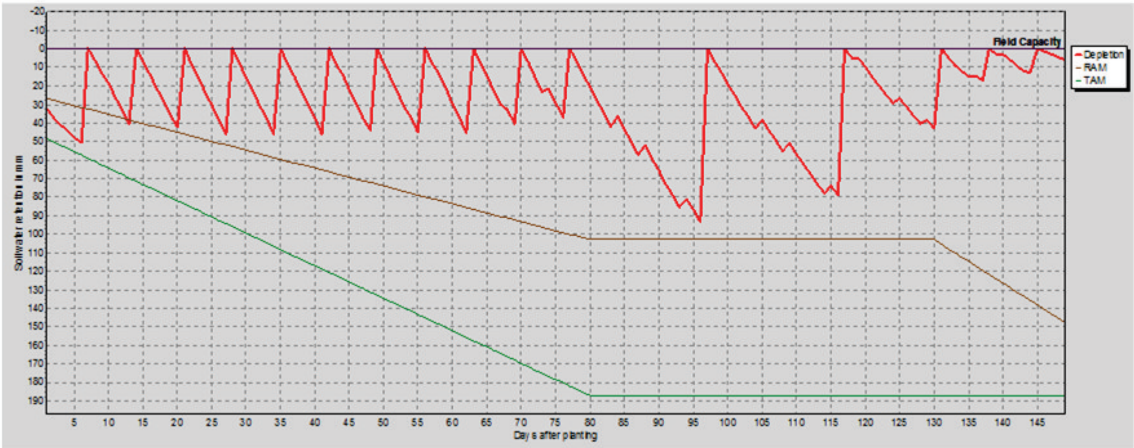
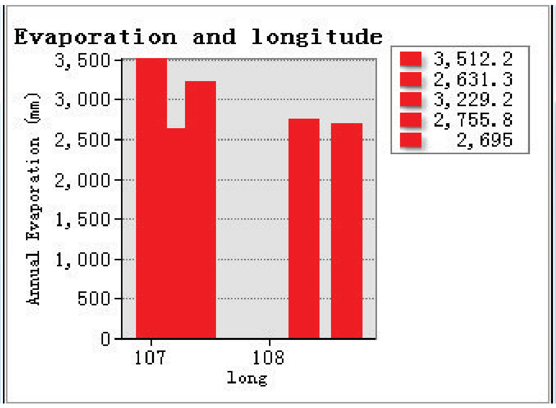


Figure 3: Irrigation scheduling with water stress imposed example of 2008



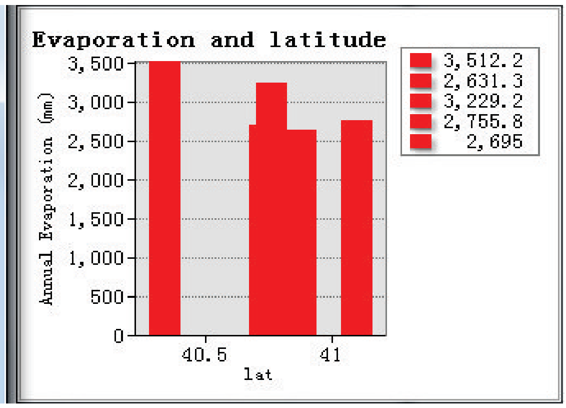


Figure 4: general trend of the Hetao evaporation

Table 3: Comparison of Irrigation Water Requirements, Yield reduction and Cropping intensity for Corn simulated in summer

	Irrigation Scheduling treatments	
Parameter of comparison	No water stress	with water stress
Total gross irrigation (mm)	1190.5	1180.9
Total Net Irrigation (mm)	833.4	826.6
Actual water use by maize (mm)	867.1	849.9
Potential Water use by maize (mm)	867.1	867.1
Yield reduction (%)	0	2.5
Timing	Irr. At 100% deplet.	Irrig. At fixed interval per stage (Interval in days: initial 7, development 7, mid 20, late 7)
Application	Refill to 100 % of field capacity	Refill to 100 % of field
Field efficiency: (%)	70	70
CROPWAT 8.0		

Table 4: water supply of the perimeter example of year 2008

Scheme Supply ET_0 station: Hanghou 2008 Rain station: Hanghou 2008				Cropping Pattern: Hh. Crop Pattern								
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Precipitation deficit												
Hhcorn 2008	0	0	0	53.2	200.8	190.2	150.5	108.6	30.7	0	0	0
Net scheme irr.req.												
in mm/day	0	0	0	1.8	6.5	6.3	4.9	3.5	1	0	0	0
in mm/month	0	0	0	53.2	200.8	190.2	150.5	108.6	30.7	0	0	0
in l/s/h	0	0	0	0.21	0.75	0.73	0.56	0.41	0.12	0	0	0
Irrigated area (% of total area)	0	0	0	100	100	100	100	100	100	0	0	0
Irr.req. for actual area (l/s/h)	0	0	0	0.21	0.75	0.73	0.56	0.41	0.12	0	0	0
CROPWAT8.0												

6. Conclusion

Spatial variation of evaporation and general trend was established using GIS for Hetao region. The adequacy of water resources has been studied in detail to enable development of net irrigation requirements for summer maize crop. Proper and optimal scheduling of irrigation using CROPWAT 8.0 enabled the efficient water use to 70%. The analysis of the water requirements revealed that from Jun to August, is a period when crop requirements for water is most important and when the irrigation is essential.

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