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Effect of Different Deficit-Irrigation Capabilities on Cotton Yield in the Tennessee Valley

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Abstract

Fluctuations in cotton *(Gossypium hirsutum, L.)* yield in the Tennessee Valley of Alabama are common and usually related to drought or irregular rainfall. A sprinkler irrigation study was established from 1999 to 2004 to evaluate the minimum design flow rate to produce optimum cotton yields and economic gain. A replicated randomized block design consisting of four irrigation treatments ranging from one inch every 12.5 days (equivalent to 1.5 gpm acre^{-1} design flow rate or system capability) to one inch every 3.1 days (6.0 gpm acre^{-1}) and a control, rainfed treatment. Daily plant water requirement was determined using soil moisture sensors and a spreadsheet-based scheduling program (MOISCOT) developed by Alabama Cooperative Extension engineers. Significant yield differences between irrigated and rainfed cotton were noted during the study period, with rainfall variability and treatment effects accounting for most of the yield response. The minimum design flow rate (1.5 gpm acre^{-1}) increased mean seed cotton yield by more than 500 lb acre^{-1} over rainfed yields. The most economically efficient design flow rate (4.5 gpm acre^{-1}) increased mean seed cotton yield by more than 996 lb acre^{-1}. A positive relationship was observed between cotton yield and total seasonal irrigation depth during dry years. Across all six years of the study, irrigated treatments produced significantly higher yields than rainfed cotton. The highest six-year cotton lint yield and net economic returns were obtained with the 4.5 gpm acre^{-1} irrigation treatment. This result provides a rule of thumb for estimating the extent of irrigated area based on available water supply rate.

Keywords: Cotton; Deficit irrigation; Irrigation system capacity; Design flow rate; Economic return

Introduction

Increased demand for limited water resources worldwide mandates that agricultural sectors explore increased water use efficiency for irrigation while striving for optimum economic crop productivity. Excessive irrigation aggravates water scarcity and can result in leaching and/or runoff of nutrients and pesticides. As a result, excessive irrigation can lead to increased costs for production and environmental protection. This research identifies the minimum level of irrigation for economic crop yield over a multiyear time span in a humid subtropical climate. Several studies in this humid region showed that cotton response to irrigation during seasons with insufficient rainfall [1-3]. Thus, an attempt was made here to study the response of cotton to deficit irrigation as a mean to conserve irrigation water while maintaining an economic yield.

Deficit irrigation has been reported by numerous authors as a method to improve water use efficiency in plants [4-7]. Bordovsky et al. [8] observed that deficit irrigation of short-season cotton using a LEPA system not only improved lint yield, but conserved groundwater on the Texas Southern High Plains. Likewise, Kirda et al. [6] reported that deficit irrigation was effective in saving irrigation water and increasing water use efficiency but did not decrease cotton seed yield. On the contrary, Steger et al. [9] reported that water stress caused by delayed post-planting irrigation reduced cotton lint yield. Similarly, in field studies conducted under rainfed and irrigated conditions, Pettigrew [10] found that moisture deficit reduced cotton lint yield by 25% in rainfed cotton. Moreover, DeTar [11] showed that deficit irrigation of cotton on a sandy soil reduced yield. The decline in yield as a result of moisture deficit in cotton plants is due to physiological impacts such as reduced root growth, decreased leaf area index, lower photosynthesis, and decreased flowering and fruiting [12-20].

Northern Alabama has abundant water for crop production based on average annual rainfall (52 inches), however the region has large inter-annual variability in rainfall with low historic rainfall during the growing season (Figure 1). Sporadic convective rainfall during the growing season makes rainfed agriculture a poor competitor to the efficiency of irrigated agriculture [21].

This research originated from the broad body of knowledge related to rain-fed and irrigated crop production and to irrigation management, especially deficit irrigation practices. Earlier work by Tyson et al. [22] led to the development of a cotton scheduling procedure entitled MOISCOT (Moisture Management and Irrigation Scheduling for Cotton). This approach utilizes long-term average crop water use data, soil moisture monitoring and precipitation data to schedule cotton irrigation timing and quantity of water applied. In this experiment, the MOISCOT scheduling procedure was interrupted to incorporate a deficit irrigation component in order to simulate various design capacities, in terms of gallon per minute per acre (gpm acre^{-1}) available

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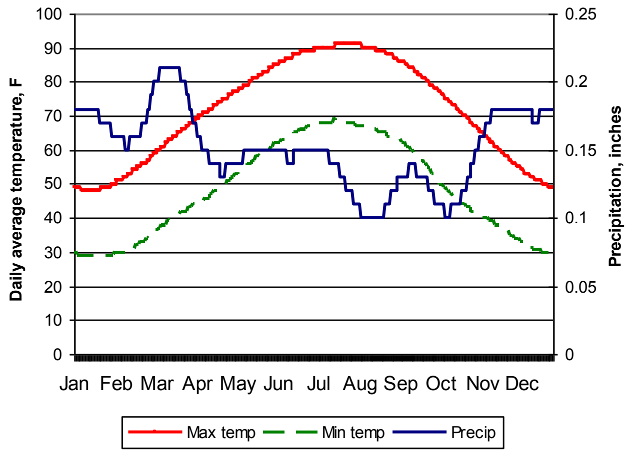

Figure 1: Long-term daily maximum/minimum temperature and precipitation, Belle Mina, Alabama, 1971-2000 (39).

for pivot irrigation of cotton. Recommended scheduling by MOISCOT was necessarily delayed when deficit irrigation capability treatments were unable to provide irrigation applications when the MOISCOT scheduling procedure called for irrigation. When extended dry periods occurred, MOISCOT would recommend irrigation but some of the capability treatments did not allow irrigation to occur because sufficient time had not passed since the last irrigation application. In terms of a center pivot system designed with a flow rate that did not meet the peak evapotranspiration rate of the cotton crop, a delay would occur from the time irrigation was called for by MOISCOT and when the system could make an application. In this case, only sufficient rainfall could return the available soil moisture in a field irrigated by the pivot to field capacity.

Because irrigation water supplies are limited on many farms, this research was designed to determine if satisfactory yields could be achieved over a number of years using irrigation systems that could not provide adequate water to replace crop evapotranspiration during peak water demand periods. The design flow rate delivered to center pivot systems is sometimes described in terms of gallons per minute per acre (gpm acre^{-1}). The desired or optimum flow rate in gallons per minute (gpm) delivered to a pivot is determined based on the anticipated crop(s) to be grown, soil type and water holding capacity, the peak water use of the crops grown, and the acres irrigated by the pivot. Dividing this flow rate by the acres irrigated determines the gpm acre^{-1}. In areas with similar climatic conditions, soil types and crops produced, this term can be used to quickly make an estimate of the flow rate needed for any size pivot. The number of acres irrigated by the center pivot multiplied by the gpm acre^{-1} is the fixed or design flow rate that will be delivered from the water source to the pivot. A higher gpm acre^{-1} flow rate may allow the pivot to match or exceed the evapotranspiration rate during peak water use periods and is preferred. A lower gpm acre^{-1} may fail to supply the peak evapotranspiration rate and thus is not preferred but may be necessary where the water supply is insufficient to provide the higher flow rate. Determining crop yield and economic benefits to a range of flow rates from low to optimum over several years is the major objective of this study.

Thus, the gpm acre^{-1} treatment levels used in this study reflect the irrigation capability of a system with the lowest gpm acre^{-1} treatment providing substantially less than the peak water demand and the higher gpm acre^{-1} treatment providing application amounts near peak. Lower gpm acre^{-1} treatments reflect the most extreme case of deficit irrigation design. A fixed flow rate is required for a specific center pivot system design. Different flow rates can be specified for a system but not changed after initial design without major design changes. Lower or deficit flow rates might be selected because of limited water supply. Thus a 100-acre system would have continuous pumping capacities throughout the growing season of 150 gpm, 300 gpm, 450 gpm and 600 gpm for each of the treatment levels.

Therefore, a system design capacity experiment was established in 1999 with the goal of determining the minimum design capacity, gpm acre^{-1}, for center pivot irrigation in Northern Alabama to produce optimum economic cotton yield. Specific objectives of the study were to 1) compare sprinkler irrigated cotton yields to rainfed with different in-season rainfall levels and distributions, 2) determine the minimum design capacity for sprinkler irrigation without impacting cotton yield, and 3) identify the economic return for varying irrigation capacities along with non-irrigated cotton.

Materials and Methods

The research presented in this paper is located in northern Alabama in the Tennessee Valley, an area of widespread cotton production. This study was conducted on a Decatur silt loam soil (fine, kaolinitic, thermic, Rhodic Paleudults) at the Tennessee Valley Research and Extension Center located in Belle Mina, Alabama, during 1999-2004.

During the six years of this study, growing season precipitation and evaporation fluctuated across a wide range, providing representative wet and dry years for comparison (Figure 1).

Treatments included four sprinkler irrigation system (Hunter pop-up rotors, Hunter Industries Inc., San Marcos, California) capacities and a control, rainfed treatment. Irrigation was managed using soil moisture sensors and a spreadsheet-based scheduling method. The irrigation system capacities tested were (1) one inch every 12.5 days, (2) one inch every 6.3 days, (3) one inch every 4.2 days, and (4) one inch every 3.1 days. The one-inch amount represented the maximum irrigation depth applied during the number of days indicated. One inch represented a typical application that could be applied by center pivot systems to the soils in this region with minimum runoff. These four irrigation capabilities were equivalent to 1.5, 3.0, 4.5 and 6.0 gpm acre^{-1} respectively. The application amount was scheduled for one inch with an electronic controller that controlled the sprinkler run time for each plot. The actual application amounts were determined based on field measurement with rain gauges placed in each treatment plot. The actual amount of water applied throughout the six-year study ranged from 0.98 to 1.15 inches. This variability reflected the mechanical and hydraulic characteristics of the sprinklers as well as wind or drift effects. Hence, an average of one inch was applied each time the MOISCOT scheduling program called for irrigation, providing that sufficient time had elapsed between irrigations for each treatment. Thus, MOISCOT might call for irrigation, but irrigation may have been delayed until the design capacity time limitation for that treatment was met. In some cases, rainfall might occur within the waiting period that would satisfy the crop requirement for ET. Thereby, the experiment provided a realistic simulation of different center pivots with different pumping capacities and flow rates irrigating a cotton field under identical rainfed conditions, but with different availability of water for irrigation. For example, a center pivot system with a lower pumping capacity per acre

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would require a longer period of time to apply one-inch than a system with a higher pumping capacity.

In order to develop a sprinkler plot layout to simulate different center pivot capacities, 39 feet x 39 feet square sprinkler research plots were designed and installed. The plots were designed to deliver water with head to head coverage in each plot area. Each sprinkler was adjusted to apply water in a quarter circle so all water applied by the four sprinklers was placed in the designated plot. The irrigation system controller for all plots had a cycle and soak feature that allowed the application of one inch in an ON-OFF cycle to each plot to ensure that applied water infiltrated in the designated plot without runoff.

The planted plot size within each square irrigated plot was 26.7 feet x 39.0 feet, equivalent to eight 40-inch cotton rows, each 39 feet long. The middle four rows within each eight row plot served as data rows and the two outside rows within each plot served as guard rows. The excess width within each plot was planted in fescue and this perennial turf grass utilized irrigation overthrow outside the area planted to cotton.

Individual plots were arranged in a randomized complete block design of five treatments. From 1999 to 2000, three replications of each treatment were used. In 2001 and thereafter, a fourth replication was added when an adjacent space became available (Figure 2).

Moisture management and irrigation scheduling was accomplished using Watermark™ soil moisture sensors (Irrometer Company Inc. Riverside, California) and the spreadsheet-based MOISCOT irrigation scheduling program developed by Alabama Cooperative Extension System [22]. The MOISCOT program was designed to use data from individual farm fields to calculate anticipated soil moisture deficits in the future and to calculate the future date when irrigation should be applied to replenish an acceptable soil moisture deficit. This program required a one-time information entry into a spreadsheet program on the irrigation system type, crop, planting date, and soil characteristics of the irrigated fields, two times per week data entry of soil moisture readings at 9- and 18-inch depth, and daily entry of irrigation and rainfall inputs. The program then calculated a date in the future to replace a projected one-inch soil moisture deficit. The Watermark™ soil moisture sensors were installed according to manufacturer's recommendations in each plot at 9- and 18-inch depths. Wedge-shaped rain gauges were installed under the sprinkler irrigation system within each plot to measure irrigation applied and another rain gauge installed adjacent to the study site to measure rainfall.

Figure 2: Sprinkler plot layout, beginning of 2001 growing season (0, denotes rainfed treatment, and 1.5, 3.0, 4.5, and 6.0 gpm acre^{-1} represent irrigated treatments). Plot size = 39' x 39'.

All plots were conventionally tilled from 1999-2002. In the fall of 2002 and 2003 wheat was planted as a cover crop. All treatment plots were converted to no-till in 2003-2004. In all experimental plots, KCl (0-0-60) and lime were applied as preplant at the rate of 60 lb K_2O and 2000 lb limestone per acre as per soil test recommendations. From 1999 to 2002, preplant nitrogen (Urea-NH_4NO_3, 32%N) was applied at 75 lb N acre^{-1} and sidedress nitrogen was applied at 30 lb N acre^{-1}. In 2003-2004, preplant nitrogen was applied at 100 lb N acre^{-1} and sidedress nitrogen at 30 lb N acre^{-1}. Nitrogen sidedressing was carried out 4 to 6 weeks after planting. In 2003, one additional ton of limestone per acre was applied, per soil test recommendations. Other cultural practices were carried out according to Tennessee Valley Research and Extension Center's practices.

Cotton (*Gossypium hirsutm*, L.) varieties selected for each year were DPL 33B (1999), DPL 428B (2000 and 2001), and DPL 451BR (2002 and 2004). Change in cotton variety during the study was required due to changes in seed technology and availability.

Cotton was planted in the second or third week of April each year using a 4-row planter on 40-inch row spacing with a seeding rate of 4-5 seeds per foot. Cotton was chemically defoliated 10 to 14 days prior to harvest by spraying the chemicals Finish (1.33 pt/acre) plus Ginstar (3.0 oz/acre). The four yield rows were harvested between the third week of September and the first week of October using a 2-row cotton picker. Each plot was harvested separately and weighed using a boll buggy (John Deere, Moline, Illinois) equipped with scales to provide accumulated mass which was divided by the harvested area to compute seed cotton yield. Turnout of lint was determined as average seasonal batch from a bulk seed cotton samples in local gin. The average turnout of lint from seed cotton for 1999-2001 seasons was 38% and for 2002-2004 was 35%. An economic analysis was conducted to evaluate irrigated cotton income gains over rainfed cotton using yield and total irrigation data per season for each irrigation capability. The sale price of $0.55/pound lint including a resale value of $200/ton seed; total annual irrigation system ownership costs of $87.95 per acre; and irrigation operating costs of $9.39 per acre-inch for a 140-acre pivot were used for the economical evaluation [23].

Yield data were analyzed statistically with a general linear model (GLM) using the LSD method for means separation at $P \leq 0.05$ [24].

Results and Discussion

Table 1 presents total amount of irrigation water applied per treatment per acre in each season. Table 2 shows average seed cotton yields per treatment per season.

In 2004, rainfall was plentiful throughout the growing season, and rainfed and irrigated yields were not statistically (P = 0.05) different (Table 2). In 2003, rainfall was near optimum through much of the growing season, but a 26-day dry period occurred between August 7 and September 4. A total of only 0.61 inches of rain occurred during this period, and this rainfall was measured in seven minor rainfall events (25). Three timely one-inch irrigation applications during this period boosted irrigated yields significantly (P = 0.05), with more than 451 additional pounds of seed cotton per acre on the highest irrigation treatments (3.0, 4.5 and 6.0 gpm acre^{-1}). The lowest irrigation treatment was not significantly different from the rainfed cotton yield (Table 2).

In 2002, irrigated yields were significantly (P = 0.05) higher than non-irrigated yield, but the highest yields were less than in other years for most irrigated treatments and were less than the 6-year means (Table 2). The reason for this reduced seed cotton yield was attributed to the very dry conditions late in 2002 growing season when the maximum application rate was not applied to meet peak water demand due to pumping problems resulting in reduced yields in all treatments. Non significant yield differences were noted in 2001 between rainfed and all irrigated treatments, except for the 4.5 gpm acre^{-1} treatment, the highest yielding treatment. Significant yield differences were measured between rainfed and all irrigated treatments in 1999 and 2000. Although 2000 and 2002 seasons had similar rainfall (Table 1), the higher yield obtained during 2000 may be related to the greater water depth applied during this dry growing season (Table 1). Rainfall variability and treatment effects accounted for the wide range of yield responses for each of these years [25]. In drier seasons, treatments with higher irrigation gave more yields than lower irrigation treatments whereas in wet seasons little or no response was observed.

Yields in the lowest irrigation design flow, 1.5 gpm acre^{-1} (1 inch every 12.5 days) were not significantly different from rainfed yields during three relatively wet seasons (Table 2). However, it is the lowest deficit irrigation design that boosted yield significantly (P = 0.05) during the dry years 1999, 2000, and 2002. The next highest irrigation design flow rates, at 3.0 gpm acre^{-1} (1 inch every 6.3 days) did not have yields significantly different from 1.5 gpm acre^{-1} in four seasons, but had an average 6-year yield significantly higher than 1.5 gpm acre^{-1} and rainfed cotton. The highest irrigation design flow rates, 3.0, 4.5, and 6.0 gpm acre^{-1} (1 inch every 6.3, 4.2 and 3.1 days, respectively) produced statistically similar yields in most of the years and resulted in 6-year average yields significantly higher than both rainfed and 1.5 gpm acre^{-1} treatments (Table 2).

When correlating seasonal rainfall with annual treatment yields, the correlation coefficient increased with decreasing irrigation capability design (Table 2), as would be expected. Similarly there was a positive relationship between cotton yield and irrigation capabilities except in seasons having sufficient rainfall (Table 2). Cotton yield responses to irrigation observed in most seasons of this study confirm similar results reported by others [1, 3, 26-31]. The results in this study stress the importance of irrigation to beneficially offset insufficient growing season rainfall. Nevertheless, other studies [27, 32, 33] reported no response to irrigation in cotton and attributed that to either insufficient irrigation applied or restricted root growth caused by soil compaction. In the present study, the absence of response to irrigation treatments observed during the 2001 and 2004 seasons is likely related to adequate rainfall during these seasons (Table 1, 2). In a similar study under similar conditions, Balkcom et al. [34] and Balkcom et al. [35] testing different irrigation regimes, found that irrigation increased seed cotton yield. Similarly, Howell et al. [36] in a thermally and rainfall limited environment such as the North Texas High Plains, found that deficit irrigation doubled cotton yield over rainfed yields. In contrast, Enciso et al. [37] reported that irrigation intervals ≤ 16 days did not influence cotton lint yield and quality using subsurface drip irrigation in medium to fine textured soils under limited water conditions. DeTar [11] also showed that deficit irrigation of cotton on sandy soils could greatly reduce yield. In a simulation study Jalota et al. [5] also showed that by reducing the amount of irrigation below the economic level, both yield and evapotranspiration of cotton were reduced to varying degrees depending on soil texture, precipitation and irrigation regimes.

Table 3 shows increasing seasonal operating costs for irrigation as depth of irrigation increased with corresponding increasing irrigation capability. Higher operating costs were associated with drier seasons (1999, 2000 and 2002) where total seasonal irrigation depths were higher (Table 1). Gross receipts and estimated net income gain above rainfed control for different irrigation capability treatments are given in Table 4. Gross receipts for lint yields above rainfed control for different

Year	Rainfall (in)	Irrigation applied per treatment (in)				
		0.0	1.5	3.0	4.5	6.0
1999	10.3	0.0	4.0	7.0	10.0	12.0
2000	7.1	0.0	6.1	11.1	12.6	13.5
2001	16.2	0.0	4.3	5.4	7.0	6.4
2002	7.1	0.0	4.9	9.9	9.9	9.4
2003	12.5	0.0	3.0	5.3	5.2	5.4
2004	15.9	0.0	3.3	4.4	5.3	6.3

Table 1: Total rainfall and irrigation per season in the experimental site.

Year	Irrigation capability (gpm acre^{-1})					R^a
	0	1.5	3.0	4.5	6.0	
	----------------- Seed Cotton Yield (lb acre^{-1}) -------------					
1999	1700c	2637b	2984b	3708a	3920a	0.99
2000	1236c	2444b	3688a	3603a	3626a	0.98
2001	3061b	3387ab	3466ab	3595a	3371ab	0.93
2002	1759c	2531b	2871a	2853ab	2925a	0.98
2003	3288b	3579ab	3802a	3764a	3739a	0.99
2004	3530a	3300a	3208a	3505a	3367a	-0.37
Mean	2490c	3002b	3331a	3486a	3470a	--
R^b	0.89	0.86	0.19	0.43	0.08	--

Means with the same letter in each row are not significantly different using LSD at P = 0.05.
R^a, R^b = Correlation coefficient for irrigation and rainfall with yield, respectively.

Table 2: Yearly and average seed cotton yields for different irrigation capability treatments.

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Irrigation capability	Total owner and operating costs ($ acre^{-1})*					
(gpm acre^{-1})	1999	2000	2001	2002	2003	2004
0.0	0	0	0	0	0	0
1.5	130	136	131	133	128	128
3.0	138	150	134	146	134	131
4.5	147	154	138	146	134	134
6.0	152	153	137	145	134	137

*Ownership costs = $119.35 acre^{-1}; Operating costs = $2.73 acre^{-1}-in.
Estimated costs include a 60-ac pivot system, with pump and motor.

Table 3: Total ownership and operating costs for irrigation capability treatments (23).

Irrigation capability	Gross receipts ($ acre^{-1})*						Net income gain over rainfed ($ acre^{-1})						Net profit
(gpm acre^{-1})	1999	2000	2001	2002	2003	2004	1999	2000	2001	2002	2003	2004	($)
0.0	--	--	--	--	--	--	--	--	--	--	--	--	--
1.5	196	253	68	148	56	-45	66	117	-63	15	-72	-173	-110
3.0	269	513	84	214	99	-62	131	363	-50	68	-35	-193	284
4.5	420	495	111	210	92	-5	273	341	-27	64	-42	-139	470
6.0	464	500	65	224	87	-32	312	347	-72	79	-47	-169	450

* Gross receipts $0.55 /pound lint (includes resale of $200/ton seed). Gross receipt = $0.55 x Turnout (Treatment yield- Control yield)

Table 4: Gross receipts and net income gain above rainfed for different irrigation capability treatments (23).

irrigation capability treatments were calculated based on a sale value of $0.55/pound lint including a resale value of $200/ton seed [23]

Net income gains over rainfed control for overhead sprinkler irrigation capabilities were estimated when the estimated ownership and operating costs were charged against corresponding gross receipts. During seasons with sufficient rainfall (2001, 2003 and 2004), sprinkler irrigation capabilities result in a negative net income gain over rainfed indicating that irrigation added unnecessary (unrecovered) costs. However, during drier seasons, cotton producers with adequate irrigation capabilities realized significant yield increases (500-1000 lb acre^{-1}) and positive net income gain (60-360$ acre^{-1}). Durham [38] reported that cotton irrigation returned high net profit even during the wetter season of 2004. Over the six-year study period, a cumulative net profit of $470 per acre was realized with an irrigation capability of 4.5 gpm acre^{-1}. Results from this study indicate that when growing season rainfall is below 12 inches, cotton producers in the Tennessee Valley of Alabama with adequate irrigation capability can realize significant yield increases along with positive net returns over rainfed cotton production. Results provide a rule of thumb of approximately 4.5 gpm acre^{-1} for estimating the extent of irrigated area based on available water supply rate.

Conclusions

In all treatments, irrigation was found to significantly increase seed cotton yield in seasons with inadequate rainfall. Data from this study indicate that the minimum design flow rate needed to produce optimum economic yields in irrigated cotton is 4.5 gpm acre^{-1} which is equivalent to approximately one inch every 4.2 days. This information can be used to optimize the design of pivot irrigation pumping plants by matching pump and storage facility size to the total area irrigated in soil type typical of the Tennessee Valley and is not necessarily applicable to other areas or soil types. Thus, cotton producers in the northern Alabama in the Tennessee Valley region with adequate irrigation capabilities can realize significant seed cotton yield increases and positive economic net returns. Results provide a rule of thumb of approximately 4.5 gpm acre^{-1} for estimating the extent of irrigated area based on available water supply rate.

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