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Optimal Irrigation and Wheat Yield Response to Applied Water

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Abstract. The production of wheat in Al-Qassim is entirely dependent on groundwater that requires high pumping lifts to supply the irrigation requiremens. Numerous studies have shown that many wheat growers over-irrigate their lands using center-pivot sprinkler irrigation systems. The most common irrigation management objective is to eliminate water as the production-limiting variable while minimizing excessive water application. The wheat yield production functions were developed to predict wheat yields for seasonal water application that ranged from 170 to 825 mm using the sprinkler line source technique. It was found that the yield increase was linear with the increase in applied water up to a seasonal applied water of about 500 mm. Above 500 mm, the relationship was curvilinear with the point of maximum yield at 734 mm. With the pumping cost of SR 0.2/cubic meter of water and SR 2000/ton grain wheat, the optimum amount of applied water was 710 mm.

Introduction

The production of wheat in Al-Qassim is entirely dependent on using groundwater that requires high pumping lifts to supply the irrigation water requirements. The average rainfall of less than 100 mm in Al-Qassim during the irrigation season is not generally considered as essential portion of the irrigation water requirements. Only when significant amount of precipitation occurs, irrigations are delayed. Center-pivot sprinkler irrigation systems are used extensively in growing wheat for their being self automated and for allowing utilization of desert sandy soils.
Numerous studies have shown that many farmers over-irrigated their crops. Estimations of actual water use on wheat crops grown in Al-Qassim range between 800 - 1100 mm, which is almost double the calculated irrigation need [1]. These figures indicated that experiments should be carried out to study the response of wheat yields to applied water levels.

The most common irrigation management objective is to eliminate water as the production-limiting variable while minimizing excessive water application.

The primary objective of the study reported here was to develop the production functions of wheat yields for seasonal water application that ranged from 170 to 825 mm at constant fertilizer level of 160 Kg N/ha. A secondary objective was to determine from field experiments the point of maximum yield and the optimum applied water.

Materials and Methods

The experiment was conducted on a one donum field at King Saud University, Qassim branch, Agricultural Research Center in Buriedah (latitude 26 degree north and altitude 625 m). The soil is sandy (43.15% coarse sand, 47.28% fine sand, 3.19% silt, 6.38% clay) with a water intake rate of about 75 mm/hr and an available soil water capacity of approximately 85 mm/m. Water well with an average electrical conductivity of 1.2 dS/m was used for all irrigations. The continuously variable irrigation treatment technique was used in this study. This technique involves a single sprinkler lateral to give a nearly triangular water application pattern with the maximum amount applied at the lateral [2, 3].

A seed drill with disc openers spaced 17 cm was used to plant 160 Kg/ha of certified Yecora Rojo seed on Dec. 15 for both 1989 and 1990 seasons. Once the crop was established, various amounts of irrigation water applied with the line-source sprinkler system. Water was applied under conditions as calm as possible to reduce wind distortion of the irrigation pattern. Fertilizer was applied uniformly in all plots, with 30 Kg of triple super phosphate applied per donum at planting and 16 Kg N/donum was divided into three equal amounts and added at seedling, tellering and heading stages.

The irrigation treatment adjacent to the sprinkler line was scheduled to receive the amount of crop evapotranspiration (ET) as calculated from class A evaporation pan, using the following water balance method:

$$I = ET - R + D_p - \Delta\theta \tag{1}$$

Where:
- I = irrigation water applied, mm
- ET = crop evapotranspiration, mm
- R = rainfall, mm
- D_p = deep percolation, mm
- $\Delta\theta$ = decrease in soil moisture, mm

Tensiometers and Neutron probe access tubes were installed at each irrigation treatment to determine $\Delta\theta$ and adjust the calculated amount of applied water to the active root zone depth. Deep percolation (D_p) was therefore minimized at the sprinkler line and was negligible at locations away from the sprinkler line. The amount of rainfall

(R) was measured with a rain gauge. Runoff was negligible because the water application rate did not exceed the infiltration rate. The amount of water applied (I) was measured with catchment cans 100 mm in diameter, which were placed at each irrigation treatment.

In 1989 season, the wheat was planted on strips 1 m wide and 50 m long. The total field plot size was 20 m × 50 m. The field plot was divided into 20 strips (1 m × 50m each) with the sprinkler line at the center as shown in Fig. 1. The ten strips on one side of the sprinkler line represented ten continuously variable irrigation treatments. The irrigation treatments on the other side of the sprinkler line were considered as replications. This field plot technique gave ten irrigation treatments with two replicates. Irrigation was stopped on April 30. Grain yields were measured on May 10. Each two strips (representing two replications) of 1 m × 50 m were cut parallel to the sprinkler line with a plot combine at each location where evapotranspiration was determined. In addition to grain yield, plant height, number of grains per head, and 1000 grain weight were also determined for each irrigation treatment.

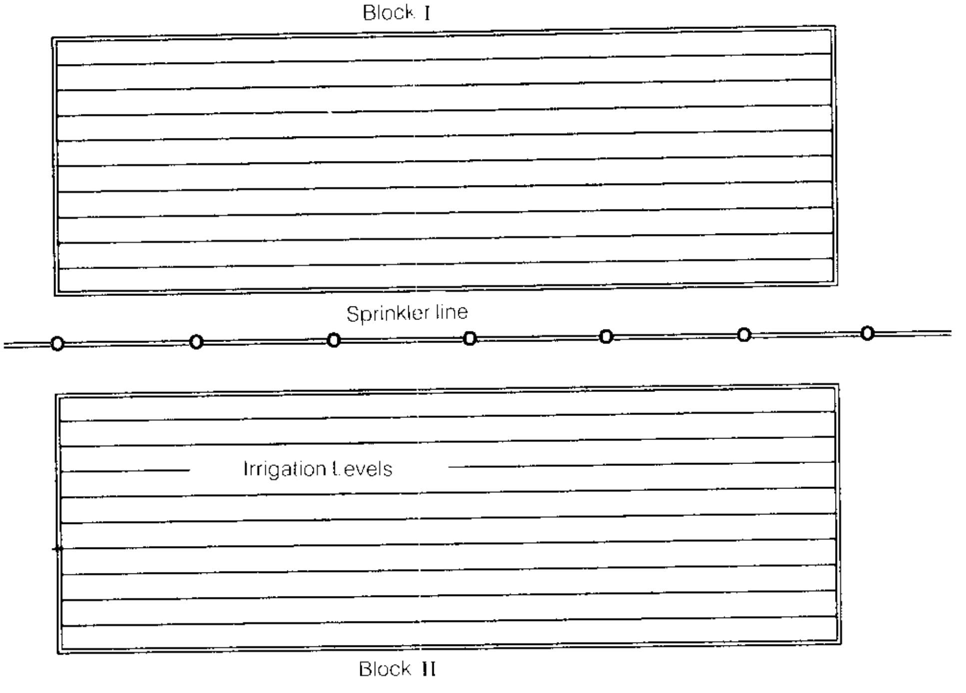
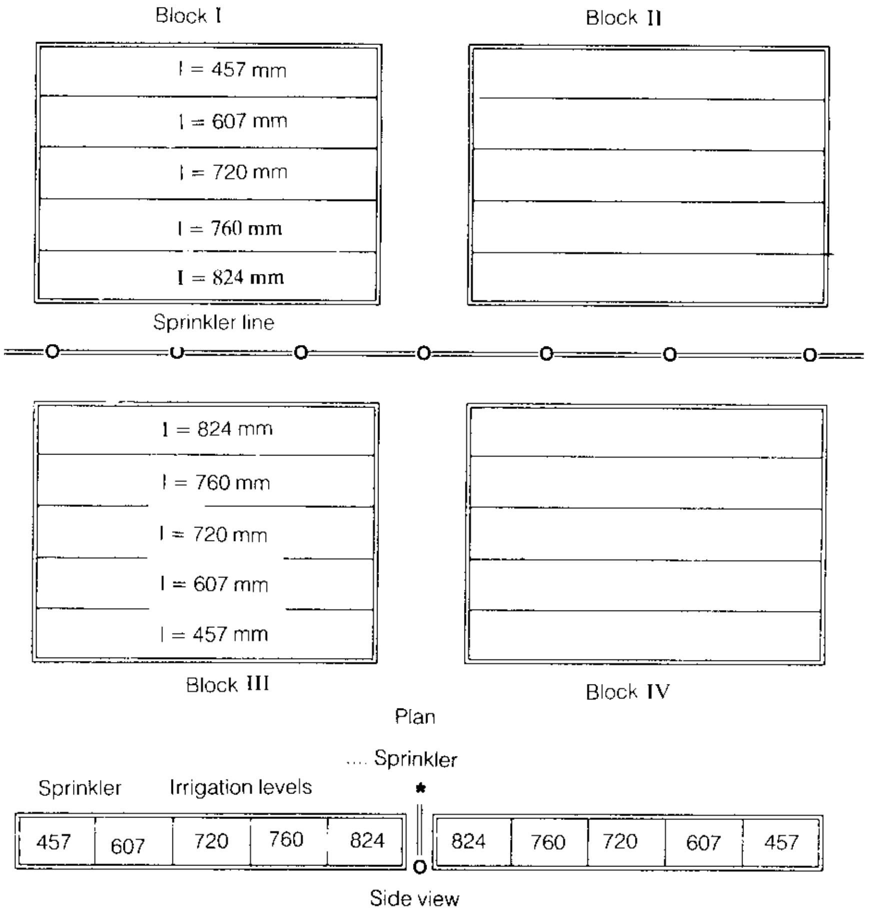


Fig. 1. Field layout in 1989 season. Ten irrigation treatments replicated two times in two blocks.

In 1990 season, five irrigation treatments were replicated four times in four blocks, utilizing the same field plot of 1989 season, as shown in Fig. 2. Each block consisted of five strips (experimental units) that were 2 m wide and 25 m long. The

Fig. 2. Field layout in 1990 season. Five irrigation treatments replicated four times in four blocks.



irrigation scheduling plan during 1990 season was changed to apply more water than in 1989 season. Therefore, the irrigation treatment adjacent to the sprinkler line was scheduled to receive 1.3 times ET as calculated from class A evaporation pan using Eq. 1.

Results and Discussion

Grain yield

In 1989 season, the ten irrigation treatments received a seasonal net water application of 169, 233, 298, 363, 410, 469, 496, 508, 517, and 521 mm. The irrigation treatments showed a significant linear relation, Eq. 3, (R= 0.8659) at .01 level of significance with grain yield at 6.2 % moisture content on dry basis. The results are summarized in Table 1 and shown in Fig. 3. The curvilinear relation, Eq. 4, was also

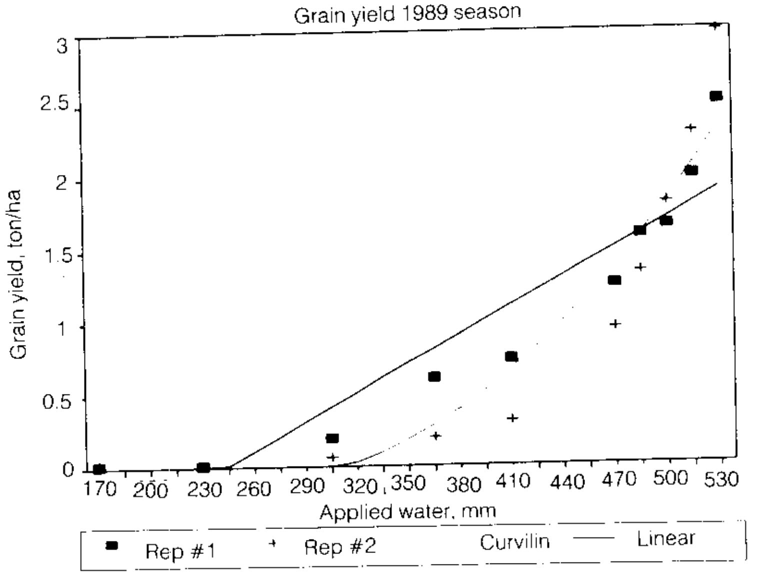


Fig. 3. Grain yield response to applied water d in 1989 season.

tested and found significant at .01 level (R= 0.9506). The linear and nonlinear regression analysis were performed using the SAS software (SAS, 1982) on a personal computer.

The general linear model presented in Table 1 was:

$$Y = a + b\,I \qquad (2)$$

where

Y = grain yield, ton/ha
I = irrigation water applied, mm
a,b = intercept and slope of the straight line.

Analysis of results showed that:

$$Y = -1.6144 + (0.66242E\text{-}2)\, I \qquad (R=.8659) \qquad (3)$$

Using a nonlinear second degree poolynomial model, with general form:

$$Y = a + b\,I + c\,I^2 \qquad (4)$$

where a, b, and c are the regression coefficients.

The analysis of the same results gave the following relation:

$$Y = 2.0602 - (0.16783\,E\text{-}1)\, I + (.32599\,E\text{-}4)\, I^2 \qquad (R= .9506) \qquad (5)$$

Although the correlation coefficient for the linear relation is less than that for the curvilinear one, the linear relation agreed well with what was found in the literature. Cole and Mathews [4] indicated a linear relation (y = a + b ET) and found that the value of the coefficient a was always negative. They also indicated that the amount of water used as ET to attain any yield is obtained from the linear relation when the yield is zero. Furthermore, they indicated that ET generally ranged from about 10 cm to 25 cm for spring wheat and that the value of the slope, b, ranged from 66 Kg/ha-cm to 132 Kg/ha-cm. In 1989 season where the deep percolation was minimized at the sprinkler line and was negligible at locations away from the sprinkler line, the intercept of Eq. 3 is negative and the slope is equal to 0.0066 ton/ha-mm (equivalent to 66 Kg/ha-cm). Also from Eq. 3, I is equal to 243.7 mm at Y equals zero which agreed with the results of Cole and Mathews [4].

Hanks [5] indicated that the value of ET is a good approximation of the amount of soil evaporation. It should be noticed that the problem of the developed wheat production functions is that it is site specific. This means that the reaction found for one site does not apply to another site because of different climatic and soil conditions in addition to the effects of timing of water application.

In 1990 season, the five irrigation treatments received a seasonal net water application of 457, 607, 720, 760, and 824 mm. The irrigation treatments showed a significant curvilinear relation (R=0.9054) at 0.01 level of significance with grain yield at 7.2 % moisture content on dry basis.

The following relation is obtained:

$$Y = -8.0719 + (3.00824\ E{-2})\ I - (2.0497\ E{-5})\ I^2 \qquad (R=0.9054) \qquad (6)$$

The results are summarized in Table 2 and shown in Fig. 4.

It can be seen that the grain yield increase is linear with the increase of applied water up to a seasonal applied water of about 500 mm, according to Eq. 3. Above 500 mm, the relation between grain yield and applied water is curvilinear, according to Eq. 6. The preceding results agree with what was found by Singh and Mann [6] for wheat grown in rainless winter months in arid northwest India. They found that the relationship between yield and applied water varied in form from a linear relationship under a low range of irrigation amounts to a convex relationship as maximum yield was approached.

Figure 4 showed that the grain yield was maximized within the range of the irrigation treatments. To obtain the point of maximum yield, the first derivative of the water response function, Eq. 6, is set equal to zero as follows:

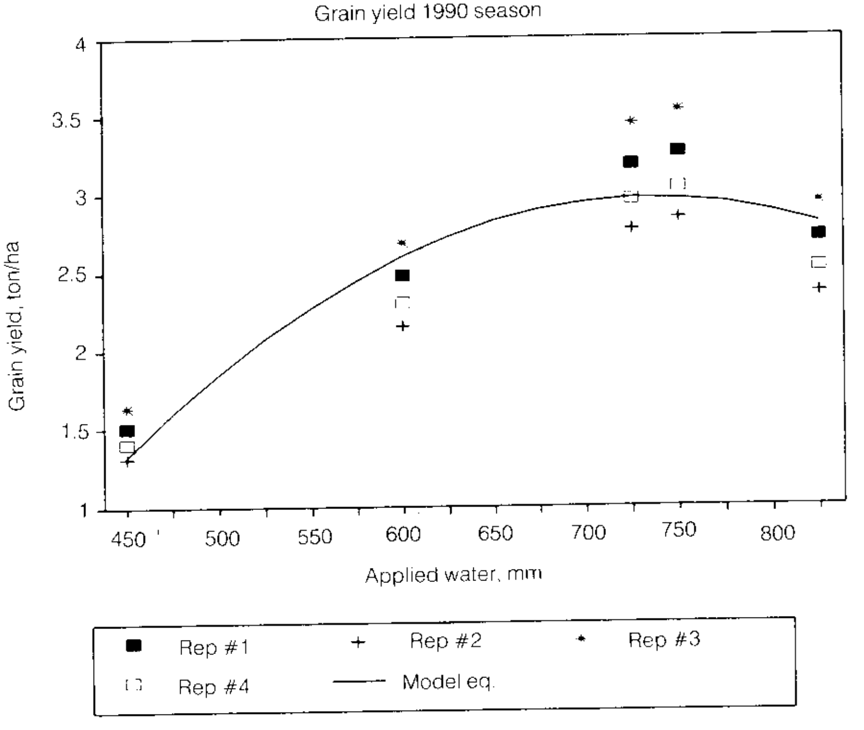


Fig. 4. Grain yield response to applied water in 1990 season.

$$dY/dI = (3.00824\ E{-}2) - (4.0994\ E{-}5)\ I = 0 \qquad (7)$$

Solving Eq. 7, yields; I = 734 mm
The optimal economic level of production for an unlimited water supply is estimated analytically as follows [7, p. 243-266; 8, 27-29]

$$dY/dI = P_i / P_y \qquad (8)$$

where

dY/dI = derivative of water response function
P_i = price of water unit, SR/ha–mm
P_y = price of grain yield, SR/ton

The price of one ton of grain wheat is SR 2000, and a 1 ha-mm of water applied costs SR 2 as calculated below. Solving Eqs. 6 and 8, the optimum applied water is: $I_{optimum}$ = 710 mm.

Table 1. Regression coefficients and statistical data for 1989 season

	Grain yield ton/ha	Plant height cm	# of seeds per plant	Weight of 1000 Grain
Regression coefficients				
a	−1.6144	16.0755	−9.5656	22.7256
b	.66242E−2	.75564E−1	.75165E−1	.0253
Standard error of estimate for reg. coefficients				
b	.902E−3	.499E−2	.951E−2	.519E−2
Correlation coefficients				
R	.8659	.9629	.8811	.7542
F value for model				
F	53.93**	229.32	62.48**	23.75**

** Significance at the 1% level.

Table 2. Regression coefficients and statistical data for 1990 season

	Grain yield ton/ha	Plant height cm	# of seeds per plant	Weight of 1000 grain
Regression coefficients				
a	−8.071886	−3.1329	−37.96667	−24.31423
b	.300824E−1	.18634	.16695	.17275
c	−.20497E−4	−.1174E−3	−.9816E−4	.10254E−3
Standard error of estimate for reg. coefficients				
b	.63E−2	.728E−1	.4789E−1	.105
c	.494E−5	.57053E−4	.37534E−4	.82298E−4
Correlation coefficients				
R	.9054	.8453	.9366	.8253
F value for model				
F	38.65**	21.28**	60.70**	12.81**

** significance at the 1% level.

As shown in Fig. 4, the crop is not immediately sensitive to water application levels above the yield maximizing level, because the yields did not respond negatively to water application amount greater than the yield maximizing level. May be this is the reason why the farmers continue to apply more water than the point of maximum yield without any yield decrease. This can be attributed to the existing sandy soil and deep water table which enabled the farmers to apply more water without any present drainage problems. Figure 4 also indicates that there is a range of relative prices (price of wheat to cost of water) in which the optimal water application occurs. As each individual farmer increases the amount of water pumped, a cost is imposed on the remaining farmers because drawing down of the aquifer leads to increase pumping costs. If irrigated wheat were irrigated at profit maximizing levels instead of yield maximizing levels, agricultural water demand would decline by a quantity of 240 m^3 for every irrigated hectar. Furthermore, if the present average applied water of 950 mm, which farmers typically use, were decreased to the 710 mm level, the irrigation water would decline by a quantity of 2400 m^3 for every irrigated hectar.

Annual pumping cost

The price of water unit is presented in this study as annual pumping cost. There are several components in total annual pumping cost according to Turner [9, p.120] and Bliesner and Keller [10, p.53] as follows:

$$\text{Annual pumping cost} = \text{Fuel cost} + \text{Maintenance and Repair costs} + \text{Annual fixed cost} \tag{9}$$

The annual fuel cost was calculated as follows:

$$\text{Fuel Cost} = \frac{T_s \times \text{BHP} \times \text{cost/unit of fuel}}{\text{BHPH/unit of fuel}} \tag{10}$$

where, BHPH/unit of fuel is the fuel conversion efficiency of the power unit expressed as brake horsepower hours per unit of fuel. The seasonal operating hours, T_s, was calculated as follows:

$$T_s = (d_n \times A) / (Q \times E_a) \tag{11}$$

where

d_n = net depth of irrigation per season.
A = irrigated field area.
Q = pump discharge (system capacity)
E_a = irrigation system water application efficiency.

The delivery costs of pumping water is calculated assuming an average well in Al-Qassim region pumping from the Saq aquifer with a static water head of 140 m. A typical

center pivot of 8–tower and 400 m radius covers 50 ha with a system capacity of 63 L/s. The annual fixed cost was calculated assuming 10 years recovery period or depreciation without interest rate. The 10 years depreciation was assumed due to the noticeable rapid corrosion of the irrigation equipments in the region. The general information on the typical irrigation system is summarized in Table 3. The initial cost of the typical system is summarized in Table 4 and the annual operating cost in Table 5.
The total annual pumping cost can be calculated by substituting the values of Eq. 9 from Tables 4 and 5 as follows:
Total annual pumping cost = 29772 + 51350 = SR 81122
The annual pumping cost was converted to annual pumping cost per unit water per unit area by dividing by the irrigated area (50 ha) and by the seasonal water applied (750 mm) as follows:
Annual pumping cost (SR/mm–ha) = 81122/(50 $\times$ 750) = SR 2.16
Therefore, the annual pumping cost of 1 m^3 of water is nearly equal to SR 0.2.

Yield components

In 1989 season, the yield components were not maximized as shown in Figs. 5,6 and 7, and indicated by the linear relationship in Table 1. The yield components considered are number of seeds per plant and 1000 grain weight. Also the plant height was measured as a good indication of water stress. The yield components are expected to stabilize at some point beyond the applied water levels of 1989 season.
In 1990 season, the irrigation treatments showed a significant curvilinear relation at 0.1 level with the yield components as indicated in Table 2 and shown in Figs. 8,9, and 10. From the regression equations presented in Table 2 for plant height, number of seeds per plant and weight of 1000 grain (gram), the maximum point was obtained by setting the first derivative of every equation equals to zero. The maximum plant height was 71 cm at 794 mm of applied water. The maximum number of seeds per plant was 33 at 850 mm of applied water which lie out of the applied water range. The maximum weight of 1000 grain was 48 gm at 842 mm of applied water which lie out of the applied water range.

It is recommended from this study that the wheat yield response function to water should be investigated under different levels of nitrogen fertilizer.

Acknowledgment: The author would like to thank Mr. Elsir E.M. Elamin for his assistance during the field experiments.

Table 3. Typical irrigation system information

Item	Information needed
1- Crop to be irrigated	wheat
2- Value of crop per ton	SR 2000
3- Seasonal consumptive use of crop	750 mm
4- Peak-use demand rate of the crop	8 mm
5- Number of hours operation per year	2238 hr
6- Type of irrigation system	Center-pivot
7- Area to be irrigated	50 ha
8- Pumping rate needed	63 L/s
9- Source of water	Well
10- Total height water is to be lifted	140 m
11- Total operating head	186 m
12- Size of power unit needed	280 bhp
13- Type of power unit	Diesel

Table 4. Initial cost and annual depreciation cost

Item	Initial cost	Annual cost
Well & casing	SR 120000	SR 12000
Turbine pump	SR 87500	SR 8750
Power unit (Diesel)	SR 76000	SR 7600
Underground pipes (PVC)	SR 14000	SR 1400
Center-pivot	SR 216000	SR 21600
Total	SR 513500	SR 51350

Table 5. Annual operating cost

Item	BHP	T_s hr	Cost/gal of fuel	BHPH/gal of fuel	Total SR
1-Fuel	280 ×	2238 ×	SR 0.4	/ 14.6	= 17168
2-Oil-engine	280 ×	2238 ×	SR 12.	/ 3000	= 2506
3-M&R engine*	SR 76000	Initial	cost × .03	× 2238/1000	= 5102
4-M&R pump	SR 87500	Initial	cost × .02	× 2238/1000	= 3916
5-M&R Irrig. Sys.	SR 216000	Initial	cost × 0.005		= 1080
Total					SR 29772

* Maintenance and repair costs/1000 hrs of operation as a percentage of initial cost are 2.0 for turbine pump and 3.0 for diesel engine.

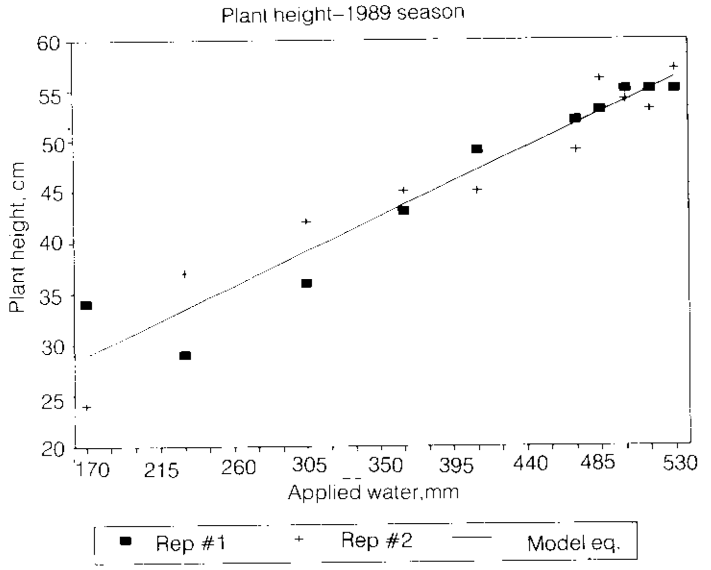


Fig. 5. Plant height as a function of applied water in 1989 season.

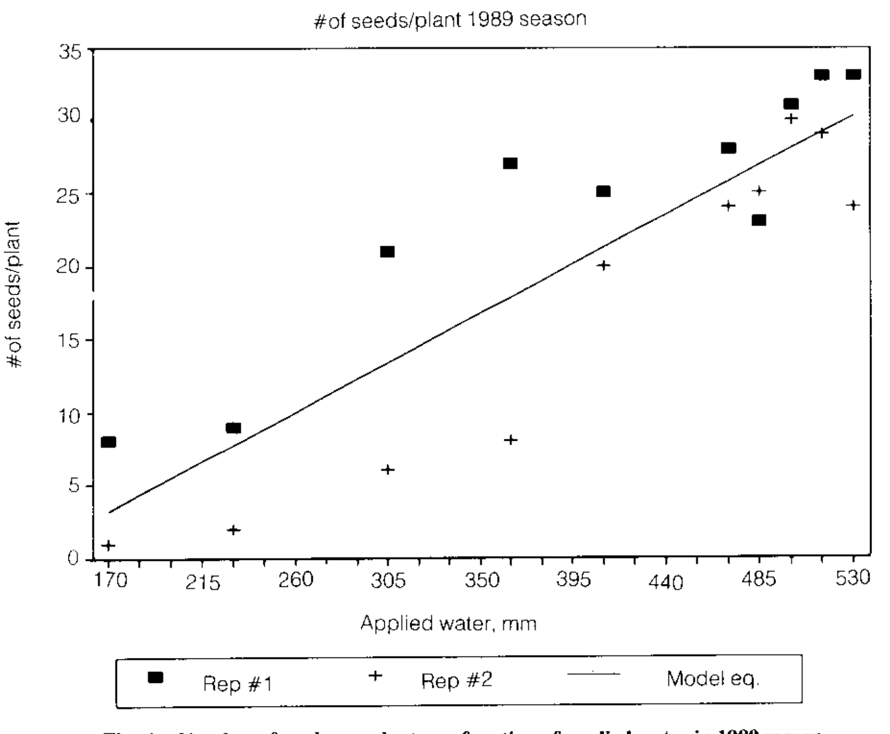


Fig. 6. Number of seeds per plant as a function of applied water in 1989 season.

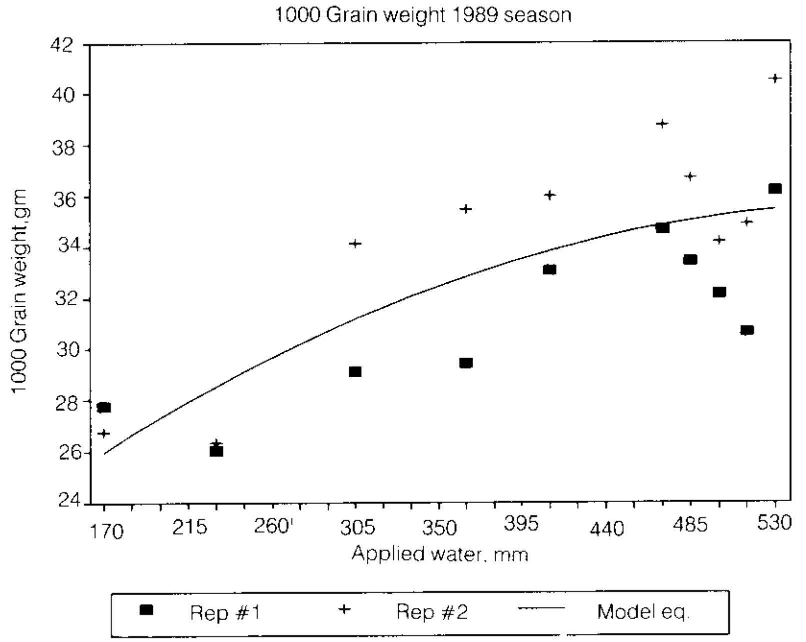


Fig. 7. Weight of 1000 grain as a function of applied water in 1989 season.

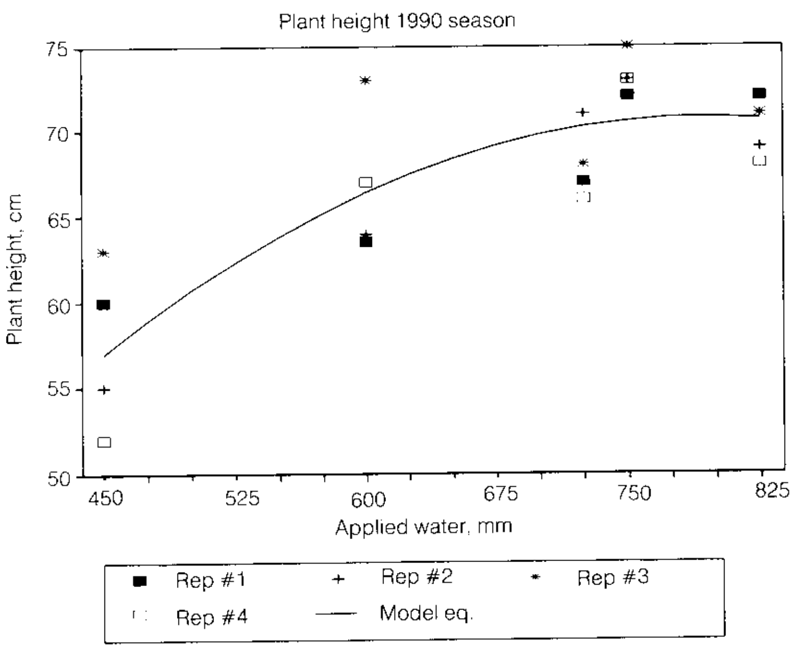


Fig. 8. Plant height as a function of applied water in 1990 season.

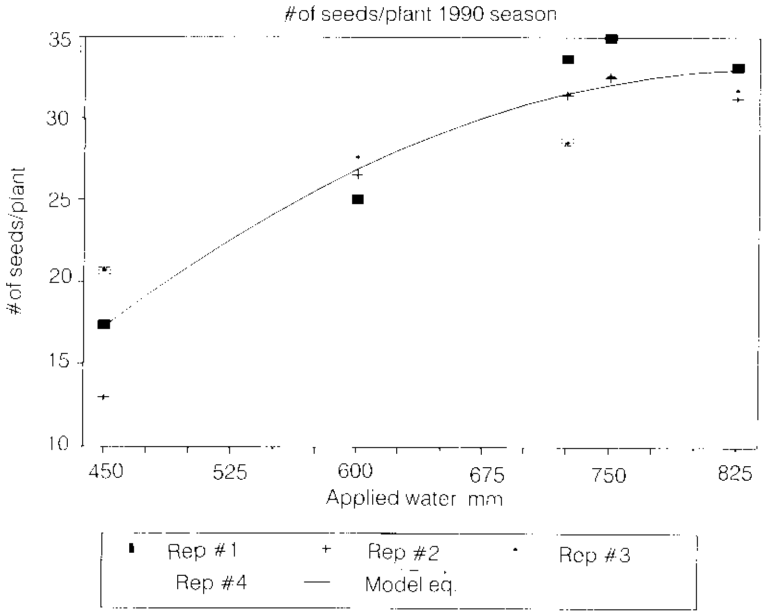


Fig. 9. Number of seeds per plant as a function of applied water in 1990 season.

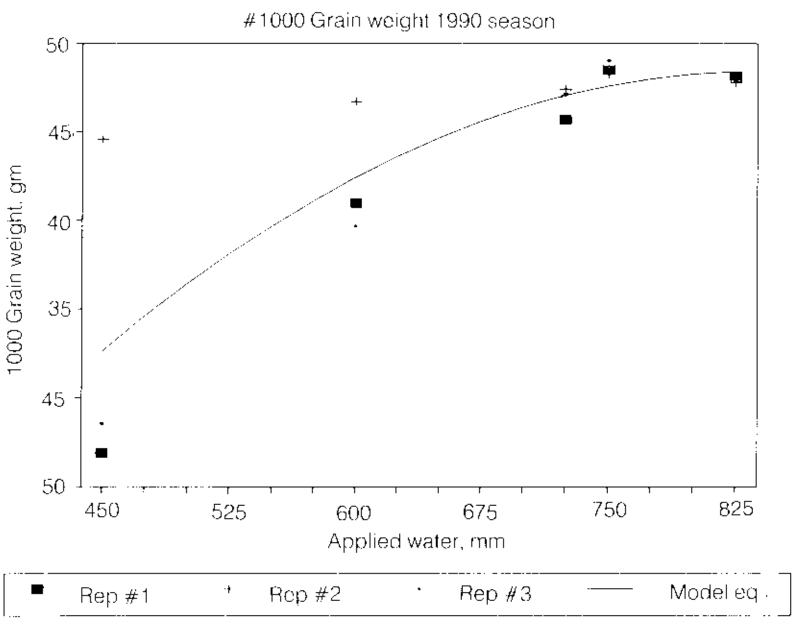


Fig. 10. Weight of 1000 grain as a function of applied water in 1990 season.

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الري الأمثل لمحصول القمح واستجابته للمياه المضافة

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ملخص البحث. يعتمد إنتاج محصول القمح في منطقة القصيم اعتمادًا كليًا على مياه الري التي ترفع من الآبار العميقة. وتشير كثير من الدراسات أن معظم المزارعين يستخدمون كميات كبيرة من الماء لزراعة القمح بأجهزة الري المحوري بهدف زيادة إنتاجية المحصول إلى الدرجة التي لا يعتمد فيها إنتاج المحصول على المياه. وقد ساعد على ذلك التربة الرملية وعدم ظهور مشكلات صرف في معظم المناطق. وقد تم إيجاد العلاقة بين إنتاجية محصول القمح ومستويات مياه الري المختلفة التي تراوحت بين ١٧٠مم إلى ٨٢٥مم عند مستوى تسميد ثابت ١٦٠ كيلوجرامًا للهكتار خلال موسمين للزراعة ١٩٨٩-١٩٩٠م، وذلك باستخدام طريقة خط الري بالرش لإعطاء كميات مختلفة من مياه الري. وأشارت النتائج إلى وجود علاقة خطية متزايدة لإنتاج المحصول من الحبوب بالنسبة لكميات مياه الري إلى المستوى ٥٠٠مم. وعند زيادة مستويات مياه الري عن هذا الحد كانت العلاقة منحنية متزايدة من الدرجة الثانية. وبلغت كمية مياه الري ٧٣٤مم عند أقصى محصول. وكانت كمية مياه الري المثلى ٧١٠مم وذلك عند احتساب تكلفة المتر المكعب من المياه بما يعادل ٠,٢٠ ريال سعودي على أساس رافع تشغيل كلي ١٨٦ مترًا لضخ المياه وثمنًا للطن من القمح يعادل ٢٠٠٠ ريال سعودي.