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Optimization of Water Use and Crop Production

In an Arid Region

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Notations Used in the Bulletin

Irr (IRR) = irrigation water applied to crop in all or part of its growing season.
ETstor = evapotranspiration derived from the plot in which water supply in 120 cm soil profile was brought to field capacity initially by a preplant irrigation.
CWS = ETstor + Irr (rainfall was nonexistent) = total water supply made available to the crop in all or part of its growing season as specified.
Eo = observed evaporation from a Class A pan evaporimeter (depth per day or per period as specified).
ET = evapotranspiration (depth per period).
ET_m = minimum amount of ET associated with maximum yield.
ET_a = actual ET derived from plot with notation ETstor.
ET_d = ET deficit, i.e. ET_m minus ET_a.
LAI = leaf area index, i.e. total leaf area (one side) per unit cropped area.
Y = harvestable yield (weight per unit area).
Y_m = maximum attainable yield under optimum water supply and the best possible management.
( ) = number of reference cited.
[ ] = equation number.
Drip-ET_{100} = drip irrigation equal to daily ET.
Drip-ET_{75} = drip irrigation equal to 0.75 ET.
Drip-ET_{50} = drip irrigation equal to 0.50 ET.
Drip-$ET_{100(s)}$ = drip irrigation with saline water equal to daily ET.
Furr-ET_{100} = furrow irrigation equal to ET.
PA = plant arrangement.
RPA = rectangular plant arrangement.
EPA = equilateral plant arrangement.
SPA = square plant arrangement.
HPA = hexagonal plant arrangement.
P = elemental phosphorus.
K = element potassium.

Introduction

In arid regions where water is limited and water prices are high, the question of its efficient use and management arises. Heavy competition from other potential water uses further threatens to reduce the volume of water available for agricultural uses. Additionally, increasing population and subsequent demand for food are facing the diminishing water resources.

From such trends it seems that crops in future will have to do reasonably well under still more water stress. Therefore, the future agricultural strategy for arid lands will have to comprise the following : (a) provision for more water according to the concepts and methods suited to arid regions, (b) integration of an improved technological base into the mode of use of the available water, (c) introduction of new irrigation technology which replaces the inefficiencies of the conventional methods of irrigation, and (d) optimizing (optimality in minimum situation) the allocation and use of the available water with continuing attempt to maximize production per unit application of water.

To improve the management of a limited water supply, introduction of unavoidable irrigation deficits (warranted by short water supply) to the cropping period becomes inevitable. Then, the optimal timing or sequencing of water deficit which results in definable minimal reduction in yield below the attainable maximum becomes important. To accomplish this requires quantitative knowledge about the relative sensitivities of the stages of the plant growth.

Identification of the optimal water deficit timings or sequences, in turn, requires some knowledge about the relation between yield and water. Much of this kind of knowledge required needs the creation of data-base from those treatment plots in which management practices are least limiting to yield. The variables, other than water, easily controllable are the fertilizer nitrogen and rate of seeding. The optimization of water use and crop production will therefore proceed sequentially through the three distinct but interrelated stages such as optimization of nitrogen and seeding rate least limiting to yield, quantification of the relationship between yield and water supply, and optimal timing or sequencing the moisture-sensitive stages of plant growth.

The approach to optimize water use in the case of one or the other crop may be important in its own right. In practice, however, several crops compete for the limited water resource on the farm. In such situation the economic interest of the farmer lies with maximization of the returns to be obtained from the use of available water supply on the farm as a whole.

The experimental results discussed in this bulletin pertain to the (c) and (d) aspects of the above proposed agricultural strategies for arid lands. No attempt is made to incorporate all published literature on similar studies conducted here and elsewhere. A few references are included where the points of interest which they pertain occur in the text.

As important as these scientific observations, are the words of acknowledgement with which we shall conclude this introduction. Authors are grateful to the former research fellow, Mr. Ram Niwas, and the laboratory and field staffs of agronomy for assistance in biometric observations and analyses of the data. The manuscript of this bulletin was typed by Mrs. K. Bhavani Bhaskaran of the Office of the Division of Soil-Water-Plant Relationship, to her we owe a special word of thanks.

Experimental Procedure

This bulletin summarizes the results of two sets of field studies. These were conducted at the Central Arid Zone Research Institute at Jodhpur, India. One, study on winter cereal and oilseed crops to provide data base required to elaborate the principles and underlying relations between yield and water use. Second, study on irrigation technology best suited to arid regions where water is limited or costly or both. The soil and climatic characteristics, common to both sets of studies, are described at one place. Experimental procedures specific to particular study are discussed experiment-wise.

Climate

The climate of Jodhpur (26° NL, 73° EL, 224 m above mean sea-level) is arid. The average rainfall is 366 mm, with ± 80% of the annual rainfall concentrated during the monsoon—July to September. Temperatures are high in summer (Apr.-June), May being the hottest month with mean maximum temperature of 41.6°C. In winter (Nov.-Feb.), rainless and calm, temperatures are mild, January being the coldest month with mean minimum temperature of 9.5°C. There are 2-3 frost nights every third or fourth year, with the surface temperature dropping to −1 to −2°C. Humidity remains low during winter to early part of summer, with afternoon values as low as 15 to 17%. It remains high (60-80%) during monsoon. Mean wind speed is more than 10 km per hour from April to June. Atmosphere remains calm during monsoon and winter seasons. Sunshine is low (6-7 hours) during monsoon, but is abundant during rest of the year. Evaporations are high in summer, moderate to low in the monsoon, and low in winter.

Soil

The soil was coarse loamy Typic Camborthid, low in nitrogen (0.02%) with a pH of 7.5 and ECe 90 micromhos/cm. Its bulk density was 1.5 g/cm^3; it had 10.4% moisture (w/w) at field capacity determined in the field and 3.0% (w/w) at 15 atm tension. The contribution of rain or ground water to the crop was nil.

EXPERIMENT 1

Field experiments were conducted on dwarf wheat (*Triticum aestivum* L. 'Kalyansona') from 1971 through 1975 in winter seasons to determine the levels of nitrogen and seeding rate least limiting to yield, optimally sequence the various stages of growth in order of relative sensitivity; and develop knowledge of the yield-water relationships. These are indispensable parameters for planning strategies for optimum use of limited water supplies. Treatment variables were water, nitrogen, and seeding rate. Each variable had five coded levels of −1.682, −1, 0, 1, and 1.682. A central composite rotatable design in three x-variables was followed (3). The quantities of inputs (rounded to the nearest whole number), in order of the five coded levels, were 10, 29, 56, 83, and 102 cm of water; 0, 61, 150, 239, and 300 kg/ha N; and 75, 95, 125, 155, and 175 kg/ha seeding rate. The plots were 5 m long and 4 m wide. Nitrogen fertilizer was drilled as urea in furrow to one side of the seed, after a preplant irrigation which assured that the season began with profile water at field capacity. Seeds were planted, on 25 November (in all years), in rows 16 cm apart. Number of plants desired was achieved by thinning. Addition of water was controlled by suitably timing and rating the irrigation and refilling the profile water storage (except the final irrigation) by applying calculated amount of water through a rubber hose. The plots with codes—1, 0, 1, and 1.682 received irrigations, respectively, at the available soil water depletion percentages in 0–120 cm soil profile of ± 70, 50, 40, and 30, which corresponded to the average intervals (days from planting to final irrigation/no. of irrigations) of 13.7, 7.8, 6.4, and 5.5 days. The crop in code −1.682 received no irrigation after planting.

Study parameters included measurements of initial soil water, depth of all seasonal irrigations, growth measured as dry matter, grain yield, and periodic as well as the seasonal total ET. Additional parameters included response to ET deficit, leaf area index, and pan evaporation. The Eo data were obtained from Class A pan located in dry field adjacent to experimental site. The observed pan evaporation values were corrected by a 0.95 reduction factor. This correction was necessary, as explained by Pruitt (21), to allow for the dry pan exposure.

EXPERIMENTAL PROCEDURE

For generating the yield-ET relationship and ordering the relative sensitivities of growth stages, Y and ET data from those plots were considered in which N and seeding rate were at code 0, least limiting to yield. This is important because if nitrogen is limiting the yield, then at that yield level one would be dealing with nitrogen production function. For, nitrogen deficiency or in excess, similarly seeding rate insufficient or excessive, may take precedence and obscure the response to water. The Y and ET on six plots with code 0 (in 1971-72 and 1972-73, the ET on one such plot was erratic, and that data were not included in the analysis), four plots with —1 coded level, and one plot each with -1.682 and 1 coded level of water were considered to represent the lower level of Y and ET. The Y and ET from the plot with 1.682 coded level of water were taken to represent maximum yield (Y_m) and maximum ET (ET_m), expressed as (100, 100). The difference between the water depletion levels when irrigations commenced in code 1 and code 1.682 was small, hence soil moisture conditions in these plots were assumed to be more or less the same. On this assumption, the data point for code 1 was included in the analysis. The purpose was to examine the extent of ET_d tolerance when the ET_d conditioning effect in the vegetative stage of the crop in code 1 was negligible. Y_m refers to the maximum level of attainable yield. ET_m is the lowest ET value relating to Y_m. Values of ET higher than ET_m may be expected but Y will remain either at Y_m or will decrease.

The ET was determined by gravimetric soil moisture measurements. This method is well adapted where "water tables are not involved, precipitation is low, and good control over irrigation water is possible" (6). The method in particular seems to be better adapted under conditions of sandy soil and arid climate. Reasons for this are : (i) sandy soil takes less time (1-2 days) to attain field capacity after irrigation, (ii) greater upward pull on soil moisture caused by higher ET demand, (iii) low unsaturated hydraulic conductivity of sandy root zone, and (iv) tendency for moisture to move upward along the temperature gradient in winter when wheat is grown. Soil moisture observations were taken from three locations in each plot at 30 cm intervals to full profile depth of 120 cm (the effective depth of this soil wherefrom the roots can extract moisture) at planting and harvest, before and after each irrigation, and on intermediate dates as considered necessary. The time schedule for all observations was similar for all years. The reported bulk density value is the mean of values for 15 locations on the experimental site, with 0.7% standard error of the mean volume weight. In winter there are little probabilities of advective effects on irrigation plots. Instead, a 0.1 ha well-watered area under wheat was put around the experimental area. In rest of the 6 ha block in which this experiment was located, mustard was grown as a general crop with two irrigations.

The actual ET_d intensities (defined later) and their effects on yield were sequenced for three time periods representing different physiological stages of wheat crop. These time periods nearly resembled the growth stages defined by Salter and Goode (24). Stage 1 refers to 4–7 weeks inclusive period of vegetative growth from the formation of primary tiller until the shooting stage (i.e. Feekes Scales II to IX, Large 1954). Stage 2 refers to 8–12 weeks inclusive period of booting/heading, i.e. a period from the end of the shooting stage to the completion of ear emergence (Feekes Scales X to X.1). Stage 3 refers to 13–17 weeks inclusive period from the opening of the flower and fertilization and grain development, i.e. from fertilization until maturity (Feekes Scales X.2 to XI). Average ET_d for the season was also determined. Hereafter the three selected time periods will be referred to as the vegetative stage, the booting/heading, and the flowering to grain formation stages respectively. The ET_d intensity for the first three weeks from planting to the crown root initiation stage was not determined, for irrigation began at the completion of this period. It was also assumed that moisture explored by roots met the crop ET demand during this period.

The ET_d intensity was expressed as % of ET_m by which ET_a fell short $(ET_d/ET_m \times 100)$ in any growth stage or time period. The reduction in yield refers to the Y_a as % of Y_m $[(1-Y_a/Y_m) \times 100)]$. The grain yield response to varying ET_d sequences was expressed as the ratio of % yield reduction/% seasonal ET_d.

EXPERIMENT 2

Other than wheat (*Triticum aestivum* L. 'Kalyansona'), crops such as sarson (*Brassica campestris* L. var. *dichotoma* Watt. 'Haryana No. 1'), sunflower (*Helianthus annuus* L. 'EC68414'), and safflower (*Carthamus tinctorius* L. 'A300') were grown simultaneously to provide the data base required for planning allocation of finite water supply to four crop alternatives. Study site, treatment variables, coded levels, experimental design, plot size, and control of border effects on treatment plots were the same as for wheat. Other common details are given by Singh and Yusuf (32). The actual values (rounded to the nearest whole number) for coded scales of the three variables for each crop (information about wheat are given earlier) are presented in Table 1.

Table 1. Actual values of water, nitrogen, and row spacing in relation to their coded scales.

Crops	Variables	Coded scales				
		−1.682	−1	0	1	1.682
Sarson	Water, cm	8	11	17	22	25
	Nitrogen, kg/ha	0	12	30	48	60
	Row spacing, cm	20	28	40	52	60
Sunflower	Water, cm	8	16	29	42	51
	Nitrogen, kg/ha	0	41	100	160	200
	Row spacing, cm	20	36	60	84	100
Safflower	Water, cm	8	16	29	42	51
	Nitrogen, kg/ha	0	20	50	80	100
	Row spacing, cm	20	28	40	52	60

The required amounts of nitrogen, supplied through urea, and uniform application of 26 kg P and 33 kg K/ha were mixed well in each plot of sarson, sunflower, and safflower, after a 7.6 cm (equal to code −1.682) presowing irrigation. Sarson seeds mixed with coarse sand and seeds of sunflower were sown in specified rows in the second fortnight of October, while safflower was sown on 5 November in all three years. Linear plant density of these crops was 20 cm. Irrigation schedules were based on critical stages, i.e. *stages of crop growth when plants are most sensitive to shortage of* water, and appearance of moisture deficiency symptoms. Measured quantities of water were applied through a hosepipe. The depths, number, and average intervals of irrigation are given in Table 2.

Table 2. Irrigation schedule for the sarson and safflower crops (sunflower received the same amount of water as safflower).

	Total water		Irrigation		Avg. Irr. Interval	
	Safflower	Sarson	Safflower	Sarson	Safflower	Sarson
Coded	cm		No.		Days	
−1.682	7.6	7.6	0	0	—	—
−1	16.4	11.2	2	1	58	57
0	29.2	16.5	5	2	26	32
1	42.1	21.8	7	3	20	30
1.682	50.8	25.4	9	4	16	23

As needed, a 0.3% solution of metasystox was sprayed to contr aphids. Sarson was harvested on 18 February, sunflower in Marc and safflower on 15 April in each year. Sundried grain weig represented the yield. In 1974-75, oil percentage of the seed w estimated using the cold percolation method (14).

The objective was to maximize the function :

$$\max z = c_1 x_1 + c_2 x_2 + \dots + c_n x_n$$

subject to :

$$a_{i1} x_1 + a_{i2} x_2 + \dots a_{in} x_n \leqslant b_i \text{ for } i = 1, \dots, m \qquad x_j \geqslant 0 \text{ for } j = 1, \dots, n$$

The resource situation was like this. The "m – 1" of the "m" constraints are weekly irrigation water. Weekly availability of water was assumed at fixed levels 10.2, 20.4, 50.8, and 253.9 ha-cm, corresponding respectively to tubewells of 2, 4, 10, and 50 thousand gallons/hour pumping capacities when run for 16 hours/day in two shifts. This fixed supply of water was, however, reduced by 20% to examine sensitivity effect of "lesser than usual" availability of water on the optimal plans. The remaining constraint limits the amount of nitrogen available. Two levels of nitrogen resource viz., unconstrained and its shortage by 50% were introduced in activity matrix for each water supply to bring the problem of nitrogen use proximate to the reality of N availability. Plant density was not constrained, since this is not an expensive input. Land charge was not included in the costs. In winter when above crops are grown, there is always more land than can be irrigated. And there is no use for this land if it is not irrigated. Equipments, labour, and other operating resources remain idle on dryland farms, which raise crops only during the monsoon season—July to September. Minimum of the wheat grain required for human consumption on the farm was constrained.

The $x_1 \dots x_n$ (1, . . ., 60) are the levels of different crop activities (there were 15 activities for each crop), each representing the treatment combination of irrigation water, nitrogen level, and seeding rate. The $c_i \dots c_n$ (i, . . ., 60) are the 4-year average return net of input and application costs from each of the 60 activities. The return (R) was determined as :

$R = P_y Y - (P_w W + P_n N + P_s S)$, where Y is yield in q/ha, P_y is the price per unit of output (Y), P_w and P_n are the prices of water and nitrogen, including associated application costs, and P_s is the price per unit of seed. The wheat grain valued Rs 115 per quintal (the procurement price recommended by the Agricultural Prices Commission), water Rs 9.85 per cm, and nitrogen Rs 2.30 per kg. Assuming that the farmer can only achieve 80% of yield obtained (as our yields may be on the higher side because of the smaller plot size and careful control of other factors affecting yields) under experimental conditions, an adjusted price (P_y=Rs 92 per quintal) was used.

EXPERIMENT 3

Studies were conducted during the period from 1972 through 1976 to evaluate the relative merits of water application by drip irrigation and conventional irrigations with respect to the yield potential and water-use efficiency of vegetable crops, water economy and use of saline water, and the effects of planting geometry on water use and economics of the drip irrigation system. Site, soil, and climatic characteristics were the same as for wheat. Objectives were accomplished in three phases.

In phase 1, the effects of drip irrigation, sprinkling at 5-day intervals (SP-5), and furrow irrigation on the yield and water-use efficiency of long gourd (*Lagenaria siceraria* (Molina) Standl. 'Pusa Summer Prolific Long'), ridge gourd (*Luffa acutangula* Roxb. 'Pusa Nasdar'), watermelon (*Citrullus lanatus* Thunb. Mansf. 'Asahi Yamato'), and round gourd (*Citrullus vulgaris* var. *fistulossus* (Stocks) Duthie and Fuller 'White Long') were studied. Effects of daily application of water by sprinkling (Sp-1) on the latter two crops were also measured. The experimental design was a randomized block replicated eight times, with blocks arranged in two parallel rows. A sheet of chicken wire 90 cm wide was erected around each block to contain the vines. The vines were trained to trail within the block to which the plants belonged. Other details are given by Singh and Singh (29).

Urea, diammonium phosphate, and muriate of potash were applied to supply N, P, and K at rates of 200, 78, and 66 kg/ha to each crop. Phosphorus and K were applied with a drill at planting time. Nitrogen was applied with the irrigation water in all treatments.

The commercial drip irrigation system made by Iplex Plastic Industries Private Limited+, Australia was used. Laterals were laid 0.9 m apart on the smoothed and flat soil surface, with 72

+Company name is for convenience of the readers and does not imply preferential endorsement by the Indian Counc. of Agric. Res.

drippers 0.5 m apart on each lateral. A 12-m square spacing of sprinklers was used on the plots irrigated by overhead water application at a line pressure of 2.11 kg/cm^2. This provided completely overlapping patterns. Each sprinkler discharged 0.74 litre/sec. The gated pipe system with gates 0.75 m apart supplied water to individual furrows. The discharge rate was 1.14 litres/sec. with the gate fully open.

Long gourd and ridge gourd were planted on 11 Mar. 1972, and watermelon and round gourd on 13 Mar. 1973 in five rows, 9 m long and 0.9 m apart with 18 plants/row on the drip irrigated plots and in six rows, 9 m long and 0.75 m apart, with 15 plants/row on the sprinkler and furrow irrigated plots. The spacings were dictated by spacings between laterals, drippers, and gates. This arrangement gave the same plant population for each crop in each system, although the ratio of row spacing to plant spacing varied. Two seeds of each crop were planted near each dripper or planting position following a 5 cm preplant irrigation where sprinkler and furrow irrigation was used and directly in dry soil where drip irrigation was used.

During the germination period, irrigation on the drip plots was based on achieving a 10 cm wet strip along the seed or plant row on each day. The water was applied on the sprinkler and furrow irrigated plots with a frequency of 2 or 3 days. The scheduling of different irrigation treatments began on 1 April. In the drip and SP-1 treatments the water with $EC = 828$ μmhos/cm was applied daily at a rate equal to 68% of Class A pan evaporation. In the furrow and SP-5 treatments irrigation commenced when the

Table 3. Total amount of water applied during the growing season on the test crops.

	Long gourd and ridge gourd			Watermelon and round gourd			
	Drip	SP-5	Furrow	Drip	SP-1	SP-5	Furrow
Water applied, cm	69†	84	84	75††	80	80	80
Averege irrigation interval, days	1	5	5	1	1	5	5
Irrigation season, days	—	98	98	—	—	61	61
No. of irrigations	—	20	20	—	—	12	12

†Preplant irrigation was omitted, 10 cm of water could not be applied.

††Preplant irrigation was omitted.

cumulative ET reached 3.2 cm, which corresponded to an average length of irrigation interval of 5 days (Table 3). It was assumed that the water distribution and application efficiencies were perfect and that it was possible to apply water at a rate equal to the computed ET. This assumption was based on the observation that the patterns of the SP-1 and SP-5 treatments were completely overlapping, that the furrow length was only 9 m, and that water application to each furrow was controlled. Water application on the SP-5 treatment was during the night and on the SP-1 treatment in the early morning. The rates of water application were measured with meters fitted into each drip assembly or based on the discharge rates of the sprinklers and the gated pipes.

Ridge gourd, long gourd, and round gourd were picked weekly, starting 41, 73, and 50 days after planting, for a total of 12, 9, and 6 pickings, respectively. Melons were first picked 73 days after planting and in all three pickings were done.

In the second phase, the effects of irrigation with sweet and saline waters applid by drip irrigation and furrow irrigation methods on the yield of potatoes (*Solanum tuberosum* L. 'Kufri Chandramukhi') were evaluated. Treatments included in the experiment were : drip irrigation equal to ET, drip irrigation equal to 75% of ET, drip irrigation equal to 50% of ET, drip with saline water equal to ET, and furrow irrigation equal to ET.

The salinity level was 3,000 μmhos/cm in the 1st year (1972-73) and 10,000 μmhos/cm in the 2nd year. The treatments were randomized in four blocks, arranged in a row. The length of lateral was 36 m which had 72 emitters, 0.5 m apart. A trial with tomato (*Lycopersicum esculentum* Mill. 'Pusa Ruby') was included with the 1973-74 experiments, viz. applications of good and poor quality water by drip irrigation equal to ET, using a paired plot design replicated eight times.

Nutrient supply included N, P, and K at rates of 250, 87, and 166 kg/ha for potato and at rates of 220, 87, and 166 kg/ha for tomato. The P and K fertilizers were applied with a fertilizer drill at the time of planting. Nitrogen was delivered with the irrigation water in all treatments. Potatoes were planted following a 5 cm preplant irrigation in five 9-m long double rows, i.e. 0.25 m between rows and 0.65 m between row pairs where drip irrigation was used, and 0.2 m between rows and 0.55 m between row pairs where furrow irrigation was used. The planting date was 23 October for both years. Seed size tubers were planted on ridges, 0.15 m apart with the drip system and 0.18 m apart with the furrow system. Tomato seedlings were planted on 21 November in five, 9-m long rows which were 0.6 m apart, with four plants/m. One drip lateral was laid on top of the ridge between the double rows of potato and along the rows of tomato. Thus, there were five laterals with a valve arrangement on each, one for each rate and quality of irrigation water treatment in each crop.

Precise scheduling of the irrigation of potato began on 7 November during both years, and for tomato on the date of transplanting. Water was applied daily on the drip irrigated plots in amounts equal to 68% of the evaporation from a Class A pan. On the furrow irrigated plots, irrigation commenced when the cumulative ET reached 3.2 cm. This value corresponded to an average irrigation interval of 7 days. The flow lengths were only 9 m. Water applications to each furrow were controlled with gated pipe. It was thus assumed that the distribution of the water and the efficiencies of application were perfect and that it was possible to apply water precisely at the ET rate. Water application rate was measured with a meter fitted into the drip assembly and on the basis of the average rate of flow through the gated pipes.

Saline water was prepared by dissolving NaCl, $CaCl_2$, and $MgSO_4$ at the rate of 40, 25, and 25 meq/litre, respectively, in water with EC=828 µmhos/cm which was stored in a concrete tank.

Water distribution in the soil was determined each day during the development and growth of the potato crop. Samples were taken from the bottom of the furrow and from the ridges between furrows. Samples for determination of soil water content were taken every morning before irrigation from the plots irrigated by drippers. The water distribution in the soil on the plots with tomato was determined by taking soil samples from different distances along and across the rows at the times when the wetted area below the drip lateral was greatest. For salinity appraisal, soil samples were taken at the end of the growing season. Salinity was determined using a 1 : 2 soil extract.

Potatoes were harvested on 22 January, in both years. Tomatoes were picked 17 times every 4 days, starting from 27 Feb. 1974.

In third phase of the study (1974–76), the treatments comprised four plant arrangements : (i) 60 cm × 25 cm rectangular, (ii) 25 cm square, (iii) 18.75 cm hexagonal, and (iv) 25 cm equilateral (see Fig. 1).

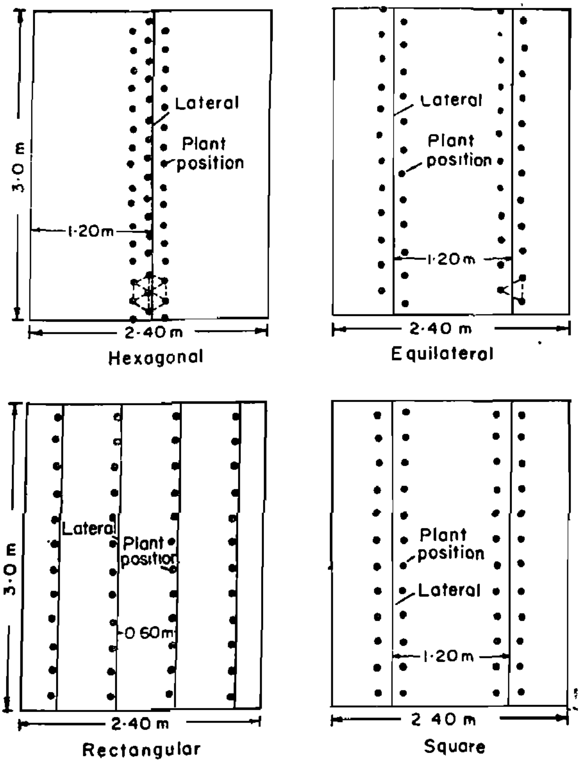


Fig. 1—Drip irrigation lateral and plant positions for rectangular, square, equilateral, and hexagonal plant arrangements.

These were evaluated in separate experiments on each of four crops, cabbage (*Brassica oleracea* L. 'Golden Acre'), cauliflower (*Brassica oleracea* L. var. *Botrytis* 'Snow Ball'), tomato (*Lycopersicum esculentum* Mill. 'Pusa Ruby'), and turnip (*Brassica rapa* L. 'Red Ball). In 1975-76, the HPA treatment with double laterals (i e., one lateral on either side of centre row of the triple rows) was also included. A randomized block design with four replications was used.

Urea, diammonium phosphate (DAP), and muriate of potash supplied 225, 87, and 166 kg/ha of N, P, and K, respectively, to each crop. In 1974-75, all the P and K and 78 kg N/ha (supplied by DAP) were drilled in a uniform manner at planting. A month later, the remaining 147 kg/ha N was applied as urea in a band 10 cm from the row and to a depth of 5 cm. In 1975-76, all the

P and K were drilled in the row at planting. The total quantity of N was applied with the irrigation water in nine equal applications every four days, beginning 12 days after planting.

The plots were 3 m long and 2.4 m wide. In each plot, there were four rows in RPA, two pairs of rows in both SPA and EPA, and one set of triple rows in HPA, with 12 plants/row in the first three treatments and 16 plants/row in the last one, thus making a total of 48 plants in each treatment. The spacings between rows were 25 cm in SPA, 21.6 cm (i.e., height of the perpendicular of a 25 cm equilateral triangle) in EPA, and 16.2 cm (i.e., height of the perpendicular of a 18.75 cm equilateral triangle resulting from positioning a plant in the centre of the hexagon) in HPA, and spacings between pairs were 95 cm in SPA and 98.4 cm in EPA (Fig. 1).

In RPA, a drip lateral (emitter type) was laid on the soil surface with zero slope along the plant row. In SPA and EPA, a drip lateral was laid in the middle of the twin rows, and in HPA along the centre row of the triple rows. Thus, there were four laterals in RPA, two in SPA and EPA, and one in HPA, with a valve arrangement on each which facilitated the application of N. Emitters on the laterals were 50 cm apart.

The crops were planted on 21 November in both years. The planting zone of the plots was moistened before the seedlings were planted. In the case of turnip, the seeds mixed with coarse sand were sown in lines. The seedlings were later thinned to maintain the above plant arrangements. In all crops the drip irrigation system was operated daily, except on Sundays. The amount of water applied was 68% of Class A pan evaporation. The water was measured by a meter fitted into the drip assembly. The flow rate of emitter was 2-litre/hour.

The width of vertical and horizontal wetting was measured in tomato, 1 day after the final irrigation. Vertical distribution of moisture was determined by taking soil samples midway between two drippers.

Turnip was harvested 80 days after planting. Cabbage, cauliflower, and tomato were harvested every 4 days, starting 70, 78, and 100 days after planting for a total of 6, 4, and 17 harvests, respectively. Heads (balls in turnip) heavier than 400 g in cabbage, 200 g in cauliflower, and 100 g in turnip were considered marketable. The number and weight of tomatoes per picking and the weight per fruit were determined for all the pickings.

Optimization of Nitrogen and Seeding Rate

Guided by security of subsistence, farmers in the Rajasthan desert prefer to grow wheat over irrigated pockets, even though a low-water-requiring crop like sarson can be an alternative choice. Since water is the scarest and costliest resource in the region, the guiding economic principle should be to maximize yield per unit application of the scarest resource—the water. To accomplish this requires that all growth factors other than water (which is limiting) should be least limiting to yield.

On nitrogen low desert soils, first of all water limits the crop yields. With the introduction of irrigation to farming system, nitrogen supply also becomes limiting. The two inputs together contribute maximum to yield only when the supplies of both are adequate (39). However in dry regions, researchers (25, 28, 37) have emphasized that the application of irrigation water in quantity lesser than the seasonal evapotranspiration should be accompanied by improved agronomic practices. particularly fertilizer nitrogen and seeding rate (5, 33). This led to the possibility as to what extent the farmers could reduce water use while maintaining or improving wheat yield by adjusting the level of agronomic practices, e.g. nitrogen and rate of seeding.

In fact, controversy abounds in the agronomic literature with regard to this possibility. Data from Bolle-Jones and Rezania of Soil Institute of Iran at Teheran (see Fig. 18 in Doorenbos and Pruitt 1975) reveal that yield of wheat tended to increase with increase in nitrogen levels, peaking at about 80 kg N/ha under adequate irrigations, 50 kg N/ha under inadequate irrigation, and 35 kg N/ha under rainfed conditions; nitrogen supply past these levels reduced yields. These data and data from other sources (12, 20) indicate that a constraint on irrigation water supply must accompany a corresponding cut on fertilizer application and seeding rate.

Other evidences on the contrary suggest that when the water supply is short the grain yields of wheat will not be affected greatly if fertilizer application and seeding rates are maintained at those appropriate for optimal water availability (5, 27, 33). In high population plantings, full crop cover develops faster whereafter water use becomes independent of planting rates (15).

Discussed in this section are : (i) yield-water use responses relationships for water, nitrogen, and seeding rate, (ii) water, nitrogen, and seeding rate interactions needed to identify reasons for divergent responses now reported, and (iii) the extent that farmers could reduce water use while maintaining or improving wheat yield by adjustment in nitrogen supply and seeding rate.

YIELD AND YIELD COMPONENTS

Variations in yield from year to year generally are considered less under irrigated conditions, unless some year turns out to be abnormal. Consequently, the regression function was calculated from average yields over four years from 1971 through 1975 (Table 4). The first and second order terms were significant (Table 5). Lack of fit term also emerged significant due largely to a low error term, as evident from high value of R^2 (0.92). Therefore, a second order surface appeared to be adequate.

Relationship with density : Yield of wheat tended to increase up to the density (code 0) giving maximum grain yield and then declined at the higher densities (Table 6). In this crop yield can be expressed as the number of heads × number of kernels per head × kernel weight. A curvilinear yield-density relationship was therefore a manifestation of an inverse relationship between density and kernel number and weight (Table 6). On the other hand, an increase in the total yield up to a density giving maximum yield was mainly through yield compensation by addition of extra heads per unit area. As soon as the density giving ceiling yield was exceeded, the gain in the total yield due to the addition of extra heads could not compensate for the loss due to the decrease in yield per plant in the process of intense intra and interplant competitions at the higher densities. The total yield then declined slowly.

Table 6 shows that the plants at low density were 178/m^2 and the yield per plant was 2.3 g, as against 249 plants/m^2 and 1.7 g yield per plant at the density which gave maximum total yield. Thus, it was the community of suppressed plants that gave the greatest yield, the greatest yield was the effect of interaction of interplant and intraplant competitions. Despite plasticity of plants the intensity of competition between and within the plants at densities exceeding the ceiling density, which gave the greatest yield, was so intense that heads/m^2 could not compensate for the loss in grain yield per plant through a gain in yield by providing extra number of heads/m^2. It seems that at densities exceeding the physical optimum the survival of plants had "precedence" over the total production of grains per unit area.

In the yield function (Table 5) the coefficient for WN term was close to significant (P - 0.1), but was not significant for WS and NS terms. These results are quite unlike the positive water-seeding rate (13) and nitrogen-seeding rate (11) interactions reported earlier

Table 4. Irrigation water applied (IRR) on the wheat crop, total crop water supply (CWS), seasonal evapotranspiration (ET), and the yield of grain (Y), all parameters averaged over 4 years from 1971 through 1975. The x_1, x_2, and x_3 denote water, nitrogen, and seeding rate respectively.

Design X_1	X_2	X_3	IRR	CWS	ET	Y
			cm			kg/ha
0	0	0	55.9	64.9	62.7	4662
0	0	0	55.9	65.3	57.7	4367
0	0	0	55.9	66.4	59.2	4497
0	0	0	55.9	65.6	57.8	4671
0	0	0	55.9	65.2	58.2	4623
0	0	0	55.9	64.8	58.3	4354
−1	−1	−1	28.7	36.5	39.6	2709
1	−1	−1	83.1	92.8	58.3	4122
−1	1	−1	28.7	35.6	42.1	2651
1	1	−1	83.1	93.4	67.6	4400
−1	−1	1	28.7	36.6	40.1	2674
1	−1	1	83.1	93.4	61.4	4105
−1	1	1	28.7	35.6	39.9	2547
1	1	1	83.1	91.6	65.5	4770
−1.682	0	0	10.2	19.8	19.0	1196
1.682	0	0	101.6	112.6	82.0	5430
0	−1.682	0	55.9	68.2	58.3	2310
0	1.682	0	55.9	65.0	61.1	4291
0	0	−1.682	55.9	65.5	57.6	3468
0	0	1.682	55.9	64.6	64.6	4393

In the low water treatment plots (e.g.—1), excess of evapotranspiration over total crop water supply came from use of soil water below 15 atm value and from the reserve in the concretionary layer below the 120 cm profile.

Table 5. Regression coefficients for yield (Y), seasonal evapotranspiration, and water use efficiency (WUE) regressed on water (W), nitrogen (N), seeding rate (S), and first order interaction terms. The W, N, and S terms are in coded scale.

	Yield, kg/ha			Evapotranspiration, cm			WUE, kg grain/ha-cm water use		
Factor	Coefficient	Standard error	Significance level of	Coefficient	Standard error	Significance level of	Coefficient	Standard error	Significance level of
Intercept	4526.80			59.1			76,6		
W	1020.52**			14.4251**			1.3986††		
		(bi)	First order terms :		(bi)	First order terms :		(bi)	First order terms:
N	299.49**	51.13	0.01	1.4938	0.67	0.01	3.1852*	0.93	0.01
S	129.61*			0.8128			1,2009		
W^2	− 420.28**			− 4.0814*			− 2.8759*		
		(bii)	Second order terms :		(bii)	Second order terms :		(bii)	Second order terms :
N^2	− 424.71**	54.83	0.01	− 0.8314	0.71	0.01	− 6.2947**	0.99	0.01
S^2	− 201.96*			− 0.3314			− 3,0072*		
WN	141.00†			1.3875			1.0750		
		(bij)	Lack of fit:		(bij)	Lack of fit :		(bij)	Lack of fit :
WS	61.50	72.31	0.01	0.3375	0.94	0.01	0.6000	1.32	0.01
NS	39.75			− 0.9875			1.7500		
R^2		0.92			0.91			0.64	

*, ** Significant at the 5 and 1% level of probabilities respectively.

†, †† Significant at P = 0.1 and P = 0.2 respectively.

Table 6. Seeding rate and equivalent plant density and four-year averages of yield and yield components of wheat.

Components	Coded scale				
	−1.682	−1	0	1	1.682
Seeding rate, kg/ha	75	95	125	155	175
Plants/m^2 at establishment, no.	178	201	249	328	356
Heads/m^2, no.	264	295	320	335	338
Kernels/head, no.	41	39	36	34	33
1000-kernel wt., g	34.5	34.2	33.9	33.8	33.9
Yield/plant, g	2.3	2.0	1.7	1.3	1.2
Yield, kg/ha	2443	2901	3233	3160	2879

in the case of nonlodging wheat. Table 6 further revealed that the yield component in water-use efficiency defining term (yield/ET) was curvilinearly related to seeding rate. Whereas the seasonal evapotranspiration was not affected significantly by seeding rate nor by interaction between seeding rate and water, and between seeding rate and nitrogen. The concept that the higher quantities of water and nitrogen would require the higher seeding rate optima (11, 13) was not supported by our results. This finding that seasonal evapotranspiration is affected neither by seeding rate nor by interactions of seeding rate with water and nitrogen led to the conclusion that a seeding rate which maximizes yield may have important implications in planning strategy for improving water-use efficiency in an arid region. This conclusion has still more relevance in context with the fact that seed, particularly farm produced seed, generally is not considered a costly input (11). Table 6 shows that maximum yield, hence maximum WUE, was achieved at the seeding rate of 125 kg/ha. Further discussion with regard to the yield-water-nitrogen interrelation was therefore pursued with the seeding rate fixed at this level.

Relationship with water and nitrogen : In the design scale for 3 x-variables, code 0 represents the centre of design, +1 and −1 represent, respectively, the upper (from code 0) and lower level of x, while 1.682 and −1.682 represent, respectively, the highest and lowest level of x. For convenience of discussion that follows, water codes above code 0 (+1 and 1.682) were arbitrarily designated as "high water treatments", water codes below 0 were designated as "low water treatments", while code 0 was designated as "intermediate water treatment".

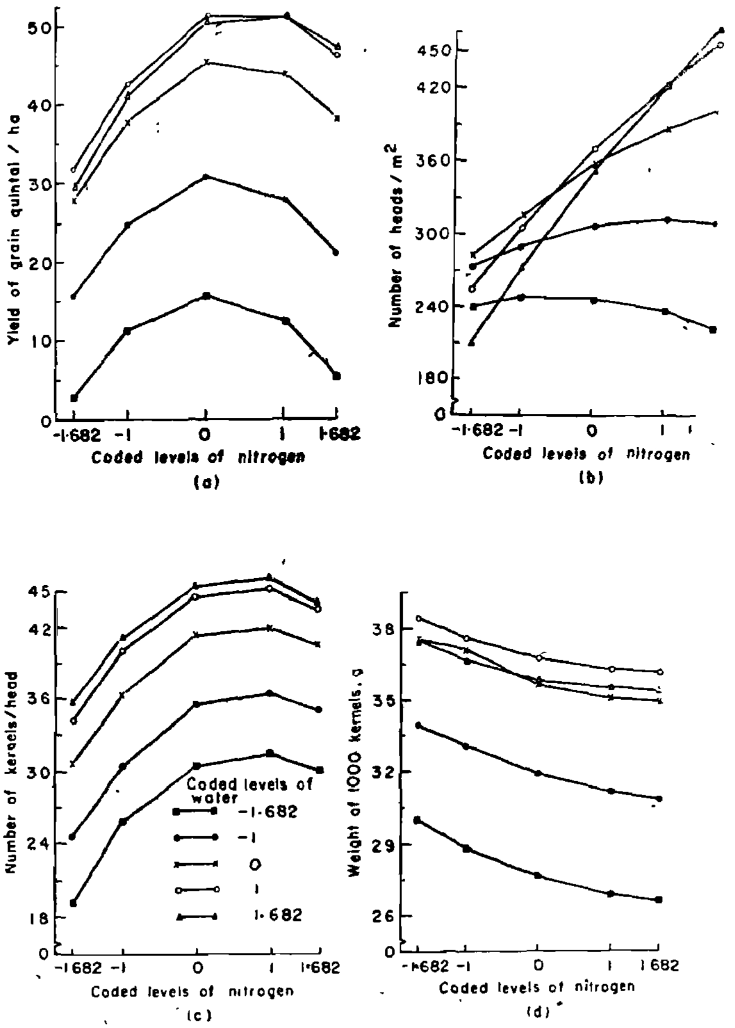


Fig. 2—Effects of significant interaction between water and nitrogen on (a) grain yield, (b) heads/m², (c) kernels/head, and (d) weight of 1000 kernels of wheat.

Fig. 2 shows that no two curves depicting yield and components of yield viz., heads/m², number of kernels/ear, and 1000-kernel weight are equidistant. This showed that interaction between water and nitrogen was present in yield and these components of yield.

Effects of water on yield and components of yield were linked with the supply of nitrogen. Yield responses to low and intermediate water treatments were considerably high at all the levels of nitrogen. Response to high water treatments on the contrary was considerably lower under no-nitrogen or low nitrogen treatment than under high nitrogen applications. A low response under high water treatments combining no-nitrogen or low nitrogen level was a combined reflection of sizeable decreases in heads/m^2 and the weight of 1000 kernels. Under these treatments, a compensating effect on yield provided by number of kernels/head could not nullify the losses in yield due to reduction in heads/m^2 and 1000-kernel weight. Thus, without an adequate supply of nitrogen high water treatment in dwarf wheat was a wasteful proposition.

Further it was observed that under all water treatments nitrogen tended to increase grain yield up to its code 0. Nitrogen supplies past this level reduced yield, due apparently to an inverse relationship between 1000-kernel weight and levels of nitrogen (Fig. 2). It seemed that any gains in total yield that could have occurred due to an increase in numbers of heads/m^2 and kernels per head under high nitrogen treatments were neutralized by a steady decrease in the weight of 1000 kernels. Another possibility may be that in high nitrogen plots late formed tillers, small in size, may have been sufficient in number to reduce the weight of 1000 kernels and subsequent yield.

Our results further showed that nitrogen level giving maximum yield (code 0) was the same for the low, intermediate, and high water treatments. This finding is quite unlike the earlier ones which have emphasised exclusively the need for a smaller rate of nitrogen under suboptimal water supply, in order to produce the highest yield. Results from this study on the contrary suggested that wheat yields will not be affected by a short water supply provided nitrogen applications are maintained at those appropriate for the optimal water availability.

As stated earlier, the aim of this study was to maximize production per unit application of water. After the identification of seeding-rate and nitrogen level each giving maximum yield in code 0 (125 kg/ha seed, 150 kg/ha N), achievement of this research goal remained a matter of mathematical computations. However, before taking up this exercise, rationality of seeding rate and nitrogen, both at code 0, with the standpoint of seasonal evapotranspiration was examined.

SEASONAL EVAPOTRANSPIRATION AND WATER USE EFFICIENCY

The coefficients for linear and quadratic terms for water in the function representing the seasonal evapotranspiration were significant (Table 5). All other linear, quadratic, and interaction terms in respect of nitrogen and seeding rate were not significant. These results indicate that contrary to the common belief an increase in the level of nitrogen or in the seeding rate did not increase the seasonal evapotranspiration of dwarf wheat. In the same way an increase in the supply of nitrogen did not require the higher rate of seeding and vice versa. By the definition of the term "water use efficiency" (yield/ET), the level of nitrogen or seeding rate that maximized the wheat grain yield, without simultaneous increase in seasonal evapotranspiration, would therefore maximize the efficiency of water use. Since the grain yield of wheat peaked at code 0 of both nitrogen and seeding rate, water use efficiency peaks (63 to 68 kg of grain per ha-cm of seasonal ET) at this coded level were obvious.

Unlike the inputs of nitrogen and seeding rate, water was curvilinearly related to seasonal ET (Table 5). Such relationship normally occurs when irrigation efficiency (ET as per cent of water applied) continues to decline as more and more water was applied. Reasons are straightforward. In frequently irrigated high water treatment plots, some water, which in low water treatments is used by the crop, remains unutilized at maturity. Early in the season when the groundcover is incomplete, excessive evaporation from the soil surface for 2-3 days subsequent to irrigation is another attribute to large part of the ET. For this reason, efficient water management requires some restrictions on high frequency irrigations during the period when the groundcover remains incomplete. Some restrictions on the amount of irrigation water to be applied is also required. Because the form of ET versus applied water relation is dependent on irrigation efficiency. This efficiency decreases as more water is applied to attain high yield. It is therefore desirable to hold application of water at some level below that required for high yield. So that conceivable losses of water in the form of percolation below the rooting zone, excessive evaporation in frequently irrigated treatments, and the probability of plant-available water remaining unutilized in the soil profile after physiological maturity are reduced to minimum or are eliminated if possible.

When it was observed that nitrogen and seeding rate at code 0 resulted in maximum yield and WUE, the 3-variable input-output relationship (shown in Table 5) was solved to one variable yield-irrigation water function, with nitrogen and seeding rate held at code 0. A graphic analysis constructed from this function was later utilized to illustrate the significance of holding irrigation water at some low level in managing a limited water supply in the arid region (see Fig. 4).

YIELD-IRRIGATION RELATIONSHIPS

The significance of yield to irrigation relationships in managing the scarce water resource on the farm will be discussed later. Here, a brief account of this aspect is given. As we know, the ET is derived from three sources—irrigation, profile water storage at planting time, and rainfall in the growing season. Together, these sources total crop water supply. Here, rainfall is not a factor in winter when wheat is grown. Included in crop water supply in this case are the profile water storage at the time of planting, plus the irrigation water.

As will be seen later, the functional relations of yield to irrigation water and yield to CWS were linear in the low range of irrigation. Under high range of irrigation, the irrigation efficiency typically reduced. This suggests that in arid region one would like to limit the seasonal irrigation to a level that results in maximum water use efficiency. This point of maximum water use efficiency occurred at about 41 cm of CWS and 32 quintal/ha of yield (see Fig. 4). Thus, the use of high-yielding variety of wheat grown at the optimum density with optimum use of N fertilizer and irrigated at some level (41 *cm of* CWS in this case) below that applied to Y_m may have important implications in rational use of a limited water supply. However, increasing water use efficiency may be desirable at an acceptable level of yield in the profitable range. Viets (39) has discussed the problems involved in obtaining increased efficiency of water use.

The problem then involved was to achieve increased water use efficiency and at the same time keep yield at an acceptable level. To accomplish this required some empirical criterion similar to the statistics generally employed to select an algebraic model. As the larger coefficient of variation, R^2, indicates an appropriate form of algebraic model fitting best to the data, so in this case the highest value of R^2 was taken to indicate the limit to minimal acceptable yield.

First of all, the quantity of CWS term (in Y versus CWS function given later) was allowed to diminish, below its predicted maximum value ($dY/dCWS = 0$), at an interval of 2 cm. Plugging each succeeding value of CWS into the function, yields were estimated until 34 steps of iteration. Iteration until 34 steps was chosen, because further iteration would bring down CWS to a level at which tall wheat or other low-water requiring crops such as mustard (*Brassica* sp.) and safflower (*Carthamus tinctorius* L.) might enter into competition with dwarf wheat for finite water resource on the farm.

To maximize $\hat{Y} - \bar{Y}$, while keeping CWS as small as possible, the deviation squares of CWS from its mean, $\overline{CWS}$, and of $\hat{Y}$ from its mean, $\bar{Y}$, were estimated. This would give large positive deviations on $\hat{Y} - \bar{Y}$ and large negative deviations on $CWS - \overline{CWS}$. The R_i^2 ($i = 1$ to 34) for each iteration was estimated as follows :

$$\text{Total Sum of Squares, TSS} = \sum_{i=1}^{n=34} (\hat{Y} - \bar{Y})^2, \text{ where}$$

$i = 1, \ldots, 34$; in this $i = 1$ represents iteration step 1 while $n = 34$ denotes the last iteration number.

$$R_i^2 = 1 - \frac{(CWS_i - \overline{CWS})^2 + (\hat{Y}_i - \bar{Y})^2}{\Sigma (\hat{Y}_i - \bar{Y})^2}$$

The R^2 continued to increase from its lowest value at iteration 1 to the highest value when CWS was at its mean value (66 cm) or close to the mean. Plugging $\overline{CWS}$ in to the Y versus CWS regression equation, yield was predictively found to be very close to $\bar{Y}$ (4,433 kg/ha). This led to the postulate that the minimal acceptable level of any resources, and so the minimum acceptable yield, would be close to the "mean" in almost every case. The authors are aware of one weakness in the estimates of the minimal acceptable level of resource use, hence the minimal acceptable level of yield. With the increase in number of iterations (n) the acceptable limit will come down to a lower value of resource or the yield. Therefore, prerequisite to rationalizing the acceptable limit to resources use, hence the yield, is to fix the iteration number first based on some sound logic or judgement.

ADJUSTMENT IN NITROGEN SUPPLY AND SEEDING RATE TO REDUCE WATER USE

In winter, water is the important constraint to bringing additional area under wheat. The data in Table 7 indicate that the yields obtained under suboptimal application of nitrogen and seeding rate can be obtained with approximately one-half of the application of water provided nitrogen application and seeding rate are managed at those appropriate for the optimal availability of water. These results suggest that a constraint on water supply must not accompany a corresponding cut on fertilizer supply and seeding rate. The finding that farmers can reduce water use at least 50% while maintaining or improving wheat yields by modest adjustment in readily available inputs such as fertilizer nitrogen and seed seems to have important implications in extending the irrigated area under the wheat crop, besides improving the production per unit application of a finite water supply. It follows that since the scarest resource in arid areas is water and so relying on water alone for attainment of higher crop yields may not be logical unless water use is combined optimally with other factors of production. Fig. 3,

Table 7. Quantities of irrigation water required to produce the given yields under suboptimal (61 kg N+95 kg seed/ha) and optimal (150 kg N+125 kg seed/ha) management of nitrogen and seeding rate.

Line+	Yield	Water required under management levels	
		Suboptimal	Optimal
No.	kg/ha	cm	
1	2,272	29	18
2	3,150	46	30
3	3,511	56	35
4	3,909	82	42
5	5,260	Imaginary	79
6	5,460	Imaginary	98
7	4,122	82	—
8	4,529	—	56

+Data in lines 1 to 6 are estimated from quadratic function between yield and irrigation applied, while in lines 7 and 8 are observed ones.

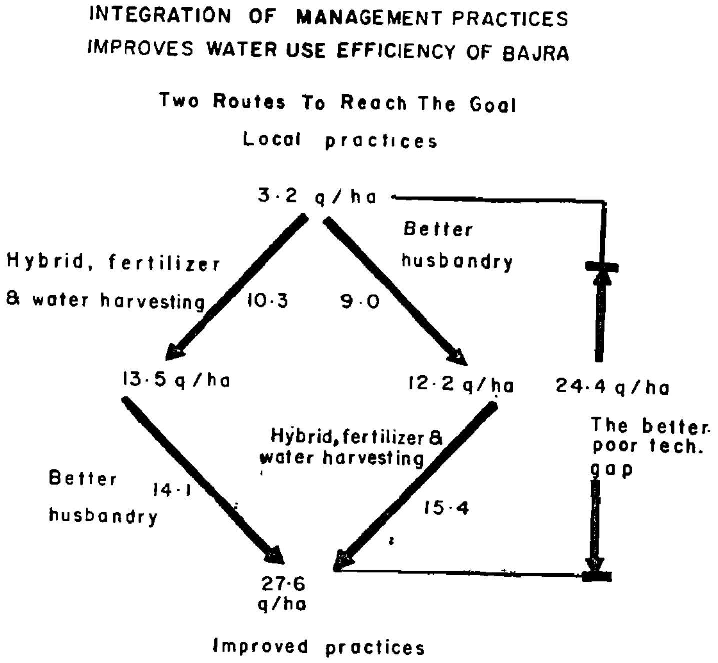


Fig. 3—Effects of integration of management technologies into the system of water harvesting on yield and water-use efficiency by hybrid bajra BJ 104.

drawn from yields of rainfed bajra for the 1977 growing season with 32 cm of rainfall, is an illustrative example. This figure illustrates how the benefits accrued from the available water supply increased many-folds under science-based practices of management.

SUMMARY

A steady increase in yield was followed by a steady decrease with applications of inputs higher than 150 kg/ha of nitrogen and 125 kg/ha of seed. These trends were apparent irrespective of the low, intermediate, or high water treatment. Therefore, the need for the lower rate of nitrogen or seeding following a constraint on irrigation water supply was not borne out. Contrary to common belief an increase in the level of nitrogen or in the rate of seeding did not increase the seasonal evapotranspiration. The level of yield obtained with the suboptimal supply of irrigation water com-

bining suboptimal rates of nitrogen and seeding could be obtained with one-half of the irrigation water, provided the nitrogen applications and seeding rates were maintained at those appropriate for the optimal water availability. Another general feature emerged was that yield potential above 3909 kg/ha was not possible at any of the irrigation water supplies combining the lower rates of nitrogen and seeding.

Yield-Water Relations and Development of Generalized Yield-Prediction Model for Wheat

Knowledge of the yield-water relationship is indispensable in planning strategies for use of a limited water supply in an arid region, where increasing population and subsequent demand for food are facing diminishing water resources. This section seeks to establish the generalized yield-water relation for wheat (*Triticum aestivum* L. 'Kalyansona') and to formulate a yield-prediction model in a form generally applicable to a wide range of crop, climate, soil, and water supply situations.

Reviewers have focused much attention on the relations of yield to evapotranspiration in a variety of crops. In container experiments, the dry matter (DM) and transpiration (T) curves have been found to be linear from the beginning. While in field studies with maize (34), grain sorghum (35), and wheat (22) Y to ET and DM to T relations have been linear from the ET-axis. A convex Y-ET function to the contrary has been reported (9, 18) in studies with tall wheat and cotton, respectively. There are exceptions in which the yield to irrigation relationships have been linear from the water-axis.

The contrasting reports from the container and field studies are mainly on two aspects of the Y-ET relationships : the "form" and the "origin" of the fitted function. This contrast seems to stem from differences with regard to : (i) crop species and varieties, (ii) definitions of "yield" and "water use", (iii) actual maximum yield attained and the value selected in place of that to represent Y_m, and (iv) selection of the data points from plots in which growth factors other than water may or may not be limited. These aspects required careful consideration in the yield-water functional analyses.

YIELD-EVAPOTRANSPIRATION RELATIONSHIP

The equations relating yield to seasonal ET (Table 8) are linear similar to linear DMandT relationship established from studies carried out in sealed containers to determine "water requirement" or "transpiration ratio" (T/DM). An important deviation is that DM-T curve passes through the origin, whereas our Y-ET curve begins from the ET-axis. The intercepts are negative, which indicate that approximately 1 to 6 cm of water was necessary in the ET process before a measurable yield of wheat was obtained.

Table 8. Relationship between yield and amount of seasonal evapotranspiration in wheat for the years from 1971 through 1975.

Year	Number of data	R^2	Intercept	Slope
			quintal/ha	quintal/ha-cm
1971-72	11	0.91	−4.3	0.78
1972-73	11	0.96	−0.3	0.71
1973-74	12	0.94	−2.5	0.77
1974-75	12	0.95	−0.6	0.74
1971-75	46	0.94	−2.0	0.75

In the crop fields, ET includes evaporation. In grain crops harvestable yield is grain, a portion of DM. Early in the season the crop cover remains incomplete. Evaporation contributes appreciably to the total ET. Therefore, Y-ET curve will be linear from the ET-axis. An exception to linearity was a convex form of the function, reported by Musick et al. (18) with tall wheat and by Grimes et al. (9) with cotton (*Gossypium hirsutum* L.). With tall wheat lodging in the higher water treatment plots reduced Y_m but did not alter the ET_m value. In cotton, the lowest value of ET associated with Y_m was 68 cm (i.e. ET_m), while in calculating the Y-ET relationship all ET values up to 82 cm had been used. Values of ET higher than ET_m could be possible, but plants apparently could use no more water than 68 cm, so that yield remained either at Y_m or decreased (see Fig. 3 in Grimes et al. 1969).

Thus, the majority of findings, including ours, are in favour of linearity between yield and ET. This relationship may have important implications in modelling the crop yields.

YIELD-PREDICTION MODEL

To develop yield-prediction model in generalized form, the actual yield (Y_a) and the actual ET (ET_a)data were transformed relative to Y_m and ET_m, taken as (100, 100). Each relative value was substracted from 100, so that the origin of the function shifted from (100, 100) to (0, 0), where ET_d was zero ($ET_a = ET_m$) so the reduction in yield was zero ($Y_a = Y_m$). Thereafter, the relationship between % reduction in yield and % ET deficits was calculated by simple regression. Like Y-ET, this relationship was found to be linear. A generalized form of the yield prediction model [1] emerged from this relationship, which was similar to Stewart's simple model (38).

$$\hat{Y} = Y_m \, [\, 1 - k. \;\; ET_d / ET_m \,] \qquad [\, 1 \,]$$

In model [1], k is a dimensionless constant (on good soils under good management the Y_m and ET_m are definable constant, so is this slop (k) of the relationship between Y_a and ET_a relative to Y_m and ET_m) which denotes yield reduction below Y_m due to ET_d. The ET_d and ET_m are the totals for the cropping period. The

Table 9. Values of Y_m and ET_m, and of k, calculated by simple regression, for one variety of wheat studied at this site and for five varieties of maize^{+} studied at Davis, Fort Collins, and Logan, U.S.A. (data for research at Yuma carried out by the University of Arizona, which looked erratic, are not included in this table).

Location	Year	Range of			Crop Variety
		k	Y_m	ET_m	
			quintal/ha	cm	
Central Arid Zone Res. Inst. at Jodhpur	1971-75	1.24-1.33	54-55	81-83	Wheat Kalyansona
Univ. of California at Davis	1970-75	1.03-1.34	112-120	60-67	Maize P3775 F4444
Colorado State Univ. at Fort Collins	1974-75	1.04-1.33	75-110	53-57	Maize NKPK20 P3955
Utah State Univ. at Logan	1974	1.27	61	64	Maize UH544A
		Avg. 1.22			

$^{+}$Data for stations other than Jodhpur are adapted from Stewart et al. (1973, 1977).

ranges of k values for wheat in this study and those for maize adapted from Stewart et al. (38) are presented in Table 9. As expected, Y_m and ET_m for the two crops tended to vary greatly but variations in k due to seasons, crop species, varieties, and locations were very small. This enhanced the possibility of estimating the mean k value (1.22, Table 9) which would apply to wheat and maize varieties studied in this as well as in earlier research (38).

This k can therefore be assumed predictable. Then, yield reduction for and selected level of seasonal ET_d is predictable; if Y_m is known, Y_a is predictable at any given site where the cultivars of wheat and maize in question are well adapted. An example as to the predictability of k from this site to another is presented (Table 10) through comparative study of grain yields of wheat in this study and of maize in research carried out at Davis (see table 10, appendix I in Stewart et al. 1973). Our table 10 did not include data for the plots in which nitrogen or plant population was stated to be limiting to yield. Relative yield was obtained by dividing the observed yield or yield computed from model [1] by Y_m of wheat or maize. In calculating relative yield, Y_m of 55 quintal/ha with

Table 10. Comparison of observed and computed relative grain yields of wheat studied at Jodhpur, and of maize studied under soil, climate, and management conditions at Davis (Calif.). Average deviation represents the mean of deviations from observed yield (i.e. $\frac{\Sigma \text{ col. 2} - \text{col. 1})}{n}$

Wheat		Maize	
Observed	Computed	Observed	Computed
1	2	1	2
0.85	0.85	0.89	0.86
0.47	0.47	0.43	0.43
0.46	0.47	0.30	0.30
0.81	0.76	0.38	0.36
0.45	0.43	0.39	0.39
0.43	0.41	0.45	0.45
0.44	0.41	0.42	0.45
1.00	1.00	0.43	0.47
		0.61	0.64
		1.00	1.00
Average deviation	−0.004	0.005	
R^2	0.99	0.99	

an ET_m value of 81 cm for wheat, and Y_m of 113 quintal/ha with ET_m value of 64.5 cm for maize were used. In relative-value terms, the right-hand side of model [1] became,

$$Y_m \ [\ 1 - k\ .\ ET_d/ET_m]\ /Y_m$$

$$\text{or} \qquad [\ 1 - k\ .\ ET_d/ET_m] \qquad [2]$$

The predicted and observed results were alike, with average deviations of a negligible order (Table 10). Our model [1] uses only one general constant (1.22) for both wheat and maize, hence seems to be better generalized so far transferability of results to other locations is concerned, than in earlier evaluations (38), which propose separate constant for each variety of maize.

To apply this model for the prediction (not necessarily in complex field trials, nor on research stations) of crop yields from available water supply in an area suitable for wheat and maize, input data on season ET together with Y_m and ET_m will be required. Under technical guidance, simple trials in progressive cultivators' fields could provide the required information.

An apprehension that no single yield expectation would exist at any given seasonal ET_d, because of different yield responses to water deficits in different growth stages or periods, may not hamper the precision of prediction. An earlier finding (22) that a "preconditioned" plant withstood more ET_d in its subsequent growth stage or period (booting/heading or flowering to grain formation stage) seems to suggest that "preconditioning" can, however, even-out the prediction error which might creep in due to growth stage effects on the yield responses to ET_d. This fact is borne out from the report of Stewart et al. (38), which underlined that a model using one seasonal coefficient gave the same results as the complex model which used different growth-stage coefficients.

YIELD-IRRIGATION RELATIONSHIPS

The linear Y-ET function implicitly assumes that irrigation efficiency (defined later) is 100%, water deficit sequences are optimal (optimal water deficit timings are that which reduce yield the least), water distribution and infiltration over experimental fields are uniform, and there are no physical and procedural constraints. These expectations, however, are not always achieved. Nevertheless, Y-ET function is thought to be a standard against which planners can predict yield from the available water supplies.

An ET value is a field level water parameter. It relates most directly to yield but only indirectly to irrigation. Irrigation is the amount of water purchased and applied. Therefore, this water is of utmost value to planners as well as to farmers. The ET is derived from three sources. These are : profile water storage at planting time, growing season rainfall, and irrigation. Together, these sources total crop water supply. In this arid belt, no rain falls in winter when wheat is grown. Hence in CWS, rainfall was not a factor. Our experimental plots received preplant irrigation each year, which charged 120 cm deep profile to field capacity. This water was treated as if it was derived from preseason rainfall conserved in the soil.

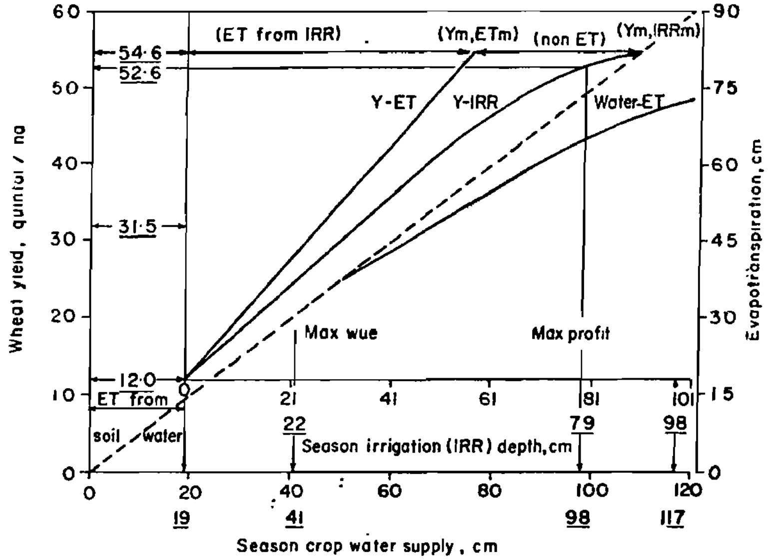


Fig. 4—Applied water-ET, yield—ET, and yield-irrigation water relationships plotted within yield-crop water supply functional relationship for wheat, averaged over four years from 1971 through 1975.

Not all Irr is converted to ET. It includes non-ET water uses, therefore Irr = ET+non-ET, and irrigation efficiency (Irr eff.) is the ET as per cent of applied water, i.e. Irr eff. = ET (from Irr)/Irr×100. Fig. 4 was constructed (based on the same 46 data points which were used for combined 1971-75 ET function) to illustrate the relationships of Y to ET and Y to Irr within the context of functional relation between Y and CWS. The relationship between total water (available soil water at planting time in

120 cm soil profile + irrigation) and the actual ET was also shown in this figure. To quantify ET and non-ET portions of irrigation, the Y-ET line was extended up to the point of ET_m. This figure illustrates reasons for a particular form of Y and Irr function, an exception to this, and the underlying reasons for the exception.

The dotted line in the figure depicts occurrence of an ideal situation where ET to total water ratio is unity. In the low range of irrigation, i.e. until 28 cm of Irr or 47 cm of CWS, the Y to Irr ($\hat{Y} = 5.85 + 0.7023$ Irr., $R^2 = 0.95$) and Y to CWS ($\hat{Y} = 2.58 + 0.6722$ CWS, $R^2 = 0.96$) relations were linear. As the season ET_m was approached to attain Y_m, Irr eff. typically reduced. The relationship of ET to total water and Y to Irr became convex. It follows that the Y to Irr relation would usually be convex, while the linearity of Y to Irr relationship would be a reality under irrigation at some level below that required for Y_m.

Application of this knowledge of Y to Irr relationships to distribution of a given supply of water will depend on whether land or water is limited or unlimited. In an area where land is limited but adequate water is available at payment of money, the objective may be to maximize the production or profit per unit area of land. The levels of Irr which maximized the production and the profit per unit area were 98 cm and 79 cm respectively. These values were determined by equating a partial derivative of Y with respect to Irr (from Y-Irr functional equation : $\hat{Y} = 1.1167\,\text{Irr} - 0.0057\,\text{Irr}^2 - 0.05$; $R^2 = 0.95$; combined for 1971-75) to zero for "maximum", and to input-output price ratio for "optimality" computation. The respective yields associated with yield and profit maximizing levels of Irr were 54.6 (our observed 4-year mean Y_m was 54.3 q/ha) and 52.6 quintal/ha. This may be termed the "maximum" or "most profitable yield" concept.

In arid regions where water, not land, limits production, the objective shifts from maximum profit to maximum efficiency per unit application of water. This point on Figure 4 was determined by the point of contact of a tangent from origin of the CWS-axis of the curve relating Y to CWS ($\hat{Y} = 1.3200\,\text{CWS} - 0.0067\,\text{CWS}^2 - 11.03$; $R^2 = 0.99$; combined for 1971–75 function). The tangent touched this curve at the coordinate : CWS = $\sqrt{a/c}$ and Y = $(2a + b\sqrt{a/c})$, in which a, b, and c are the same as in equation relating Y to CWS. This point of contact occurred at about 41 cm of CWS and 32 quintal/ha of yield, or 1 kg of wheat for 0.8 m^3 of CWS.

Graphic analysis (Fig. 4) also reveals that where the functional relations of Y to CWS joined, the irrigation was zero and whatever ET derived was entirely from soil water in storage at planting. From the point of junction upward, the Y versus CWS function became the Y versus Irr. The horizontal distance from the point ($Y_m - ET_m$) to the point ($Y_m - IRR_m$) quantified the non-ET disposition of irrigation. Whereas the distance from the point ($Y_m - ET_m$) to the point of Y_m at the ordinate of Y versus Irr indicated the ET derived from the irrigation water alone.

SUMMARY

The Y to ET relationship was linear. Origin of this curve from the ET-axis indicated that in the ET process grain crops would require substantial amounts of water before a measurable yield is obtained. In comparison, the Y to Irr relationship varied in form from linearity under a low range of irrigation to convexity under irrigation applied to Y_m. Thus in arid regions, irrigation in wheat at some level (41 cm of CWS, in this case) below that required for Y_m seems to have particular promise for a rational use of limited water supply. The relationship between % Y reduction and % ET_d resulted in a slope (k value) believed to be a genetically reproducible character. Comparison of k values for this variety of wheat and of several varieties of maize revealed a possibility of selecting a generalized k value of 1.22. Comparison of observed yields of the two crops with those predicted using the k value showed a close agreement, with mean deviation of a negligible order (0.005). These results indicate the possibility of using a generalized slope of Y/Y_m and ET_d/ET_m to additional maize and wheat varieties, possibly also to other crops.

Moisture-Sensitive Growth Stages of Dwarf Wheat and Optimal Sequencing of Evapotranspiration Deficits

The working hypothesis for this section is that different sensitivities of growth stages are a reality, and some patterns of the same total evapotranspiration deficit may reduce yield more than do others. Then, it should be possible to so manage a limited water supply that the resulting ET_d coincides with those stages which influence yield the least. To accomplish this required a quantitative knowledge about relative sensitivities of various growth stages of the wheat crop.

From an extensive review of literature relating response of wheat crop to water at various stages of growth, Salter and Goode (24) have listed clearly the various "critical growth stages" in the life cycle of the wheat plant. However, the sensitivities of various growth stages to stress have been variable, depending upon the soil conditions, weather factors, variety, plant type (tall or dwarf), and the period of maturity. The rating as to relative sensitivities has been qualitative (e.g. "more sensitive", "highly sensitive", "critical period", "greatest or most critical", "best treatment", "increased yield", "reduced yield"). In planning strategies for efficient use of limited water supplies, the response to an ET_d at the jointing stage, the heading stage, or the early grain development stage is important.

YIELD-ETDEFICIT RELATIONSHIP

The relationships found between wheat grain yield and the seasonal total ET in the years from 1971 through 1975 are shown in Fig. 5. The Y_m of wheat variety under study ranged from 53.8 to 54.7 quintal/ha. This fairly narrow range led to the postulate that for each crop variety and location a range of weather conditions exists in which top yields on a good soil under good management should fall within a rather narrow range. Some reduction in yield from Y_m resulted as more ET_d were introduced. As seen from the scatter of data points, reduction in yield was brought about by : (i) unavoidable seasonal ET_d (warranted by short water supply) intensity, and (ii) suboptimal ET_d timings with respect to growth stages.

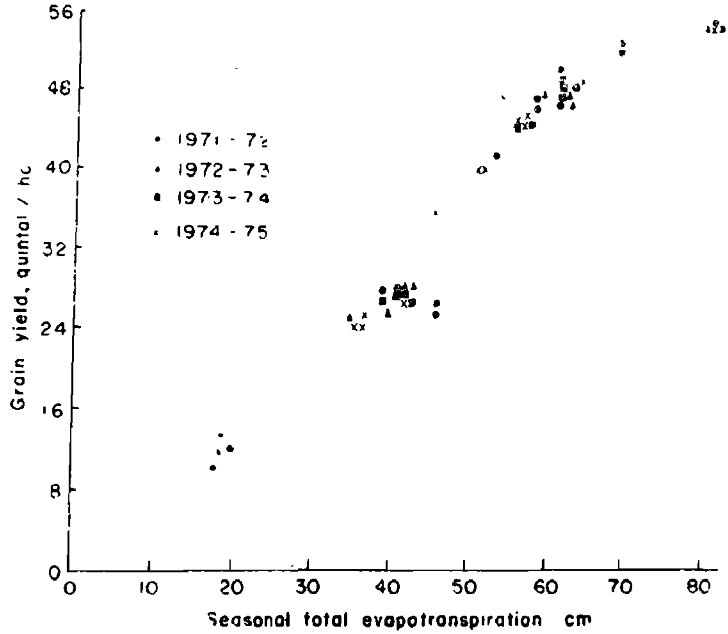


Fig. 5—Yield and evapotranspiration relations of wheat crop found in four years of a field study.

In mechanism (i), the three well known phases of yield formation in wheat, e.g. the size of nutrient absorbing and photosynthesizing surface; formation of floral organs and kernel size and number; and production, accummulation and translocation of assimilates may have been affected. Data are too limited to indicate which of the three phases of yield formation and to what extent they were affected by water deficits. In wheat, yield is composite of number of heads, number of kernels per head, and weight per kernel. The effects of ET_d must be reflected in these yield components. This was verified from yield component analysis (Table 11).

Table 11. Yield components of dwarf wheat as influenced by various levels of irrigation, with N and seeding rate fixed at code O, least limiting to yield.

Yield components	Levels of water (coded)			
	−1.682	−1	0	1.682+
Tillers per plant, no.	2.0	3.0	3.0	3.0
Heads per plant, no.	0.9	1.2	1.3	1.4
Kernels per head, no.	29.0	35.0	41.0	46.0
1000-kernel weight, g	28.0	35.0	36.0	36.0
Length of head, cm	8.0	9.1	9.4	9.6
Infertile spikelets per head, no.	4.0	3.0	2.0	2.0
Leaf area index as on 29th Jan. (boot stage)	2.3	3.3	3.3	4.6

+Coded scale 1.682 of water was taken as base for comparison.

In table 11, code 1.682 represented Y_m, ET_m plot, a base for comparison. Data for code 1 are not given, since ET_d in this code was of negligible order. The data indicate that important component limiting yield was kernel number. The weight of individual kernels did not decline until plants experienced an intense ET_d (season average 77%, Table 12) in code −1.682. The vegetative stage and the period after the grain reached the soft dough stage were therefore not sensitive to ET_d. On the contrary, the crop was moisture-sensitive during its development of floral

Table 12. Mean ET_d intensities for the three stages of growth as well as for the season, and effects of ET_d on grain yield of wheat. ET_d and reduction in Y are relative to ET_m and Y_m taken as (100, 100).

Coded scale of water	Observed yield	Seasonal ET	Mean ET_d intensity				Reduc. in yield
			Vegetative stage (4-7 wks)	Booting/heading (8-12 wks)	Flowering to grain formation (13-17 wks)	Season avg.	
	kg/ha	cm	%				
−1.682	1,196	19.0	54	86	93	77	78
−1	2,645	40.4	26	55	71	51	51
0	4,525	58.0	15	34	39	29	17
1.682	5,430 (Y_m)	82.0+ (ET_m)	17.0	31.2	28.4		
			(periodic ET_m in cm)				

+Inclusive of 5.3 cm ET_a for 1–3 weeks inclusive time period in which ET_a (for all water treatment) was equal to ET_m, and ET_d was zero.

organs (booting, heading, and flowering stages). Further details as to relative sensitivities of growth stages under consideration are discussed later.

Water deficits produced results discussed above by affecting the physiological processes and conditions which control plant growth and finally the yield. Take, for example, differentiation of spikelets. This plant process, which establishes the potential head size, takes 20 to 25 days after planting to complete (5). In this time period ET_a was equal to ET_m and ET_d was zero. As a result, length of head was not affected (Table 11). We now relate the expansion of crop canopy to ET_d. Our data indicate that an ET_d intensity of 51% (code −1, Table 12) did not limit the leaf area index (Table 11).

The plot with code − 1 received irrigations as soon as the available soil water depletion reached 70%. In all six irrigations were given. The first 3 irrigations coincided roughly with crown root initiation, early tillering, and late tillering stages. The ET_d intensity in vegetative period comprising these stages (weeks 4-7) was only 26%, therefore the tillering was not affected. The 4th irrigation coincided with the time when the flag leaf sheath had fully swollen due to growth of inflorescences. Hence head-bearing tillers were also not affected (Table 11). The 6th irrigation (final one) incidently coincided with the soft dough stage. The available soil water depletion following this irrigation measured 51 per cent 12 days after the soft dough, and 56% at the time of harvest. Winter wheat usually takes one week to reach from its soft dough to stiff dough stage (41). In one week, which the crop took to reach from soft dough to stiff dough stage, available soil water depletion may not be expected to exceed 35 to 40%. Such moisture conditions may not limit the availability of assimilates and their translocation to developing kernels. The trend of data representing the 1000-kernel weight (Table 11) bears this fact out.

Waldren and Flowerday (41) report that winter wheat takes 7 to 10 days to complete the emergence of the inflorescences. First the inflorescence of the main culm reaches anthesis. Then tillers complete anthesis. From anthesis of the inflorescence of the main culm until about half the inflorescences reach anthesis, the crop takes one week. Another one week time is required, according to these researchers, to reach the stage of complete anthesis. Thus from the time of emergence of the inflorescences, when the 5th irrigation was applied, to the time the inflorescences reached complete anthesis two weeks time had elapsed. It follows that during the last two-three days, before the final irrigation at the soft dough stage, the crop in its anthesis period may have experienced intense moisture stress, which alone appears to be a cause for substantial reduction in kernel number, possibly due to floret abortion. Data on number of infertile spikelets lend support to this presumption.

Viewed in terms of the "critical growth stage" concept, our results suggest a little modification in irrigation timings. This suggestion seems to be applicable when one has control on water application timing. The available soil water depletion, stated earlier, at the time of harvest was 56%. It means that 44% of water at field capacity remained unused in soil profile. This "plant available" water goes waste, if no crop is grown after wheat harvest. To use it fruitfully, the 6th irrigation may be advanced at least a week, in order to avoid moisture stress during anthesis and also subsequent grain filling. However, this possibility needs further study.

In code −1.682, the photosynthetically active area (at boot stage) had reduced due to senescence of lower leaves. Since foliage below the flag leaf has not been found to contribute to grain yield in wheat, reduced leaf area at the boot stage may be a factor not crucially concerned with yield. Thus, a 78% decrease in grain yield in code −1.682 could be attributed to abortion of florets which limited kernel number, and to nonavailability of assimilates to heads which limited the kernel weight (Table 11).

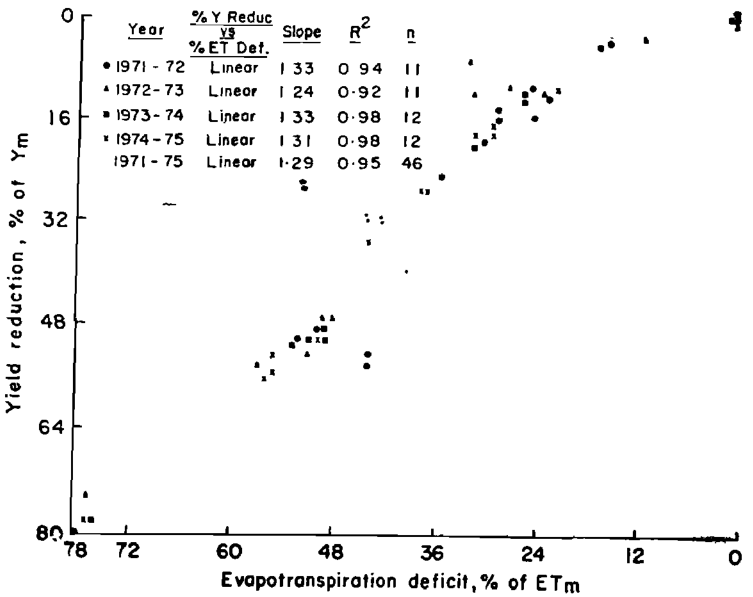
Reduction in yield through mechanism (ii) was evident from the scatter in yield at a given seasonal ET (Fig. 5). An "F" test applied to the data revealed that scatter in yield was not due to random error. Then, it may have occurred due to "suboptimal" timings of ET_d with respect to growth stages. It is in this context that the question of optimal timing of desired ET_d becomes important, especially in areas with limited water supplies.

CRITICAL GROWTH STAGES AND OPTIMAL SEQUENCING OF ETDEFICITS

To illustrate this point of interest, the data in Fig. 5 were transformed relative to Y_m and ET_m, taken as 100, and Fig. 6 was constructed. Each relative value was substracted from 100, which has the advantage of shifting the origin of the function from (100, 100) to (0, 0), i.e. to the point where the seasonal ET_d is zero ($ET_a = ET_m$). This figure shows the yield possible at various ET_d

levels, from no reduction, $Y_a = Y_m$ where $ET_a = ET_m$, throughout the yield range of interest.

Studies on this variety of wheat by Ram Niwas (22) have demonstrated that for the optimal ET_d timing the Y to ET relation was linear. Therefore the relationship between yield reduction and ET_d was linear (Fig. 6), equation [3]



Year	% Y Reduc vs % ET Def.	Slope	R^2	n
• 1971-72	Linear	1·33	0·94	11
▴ 1972-73	Linear	1·24	0·92	11
▪ 1973-74	Linear	1·33	0·98	12
× 1974-75	Linear	1·31	0·98	12
1971-75	Linear	1·29	0·95	46

Fig. 6—Effect of evapotranspiration deficits on yield reductions of wheat crop, expressed in relative value terms.

$$(1 - Y_a/Y_m) = b_0\,(1 - ET_a/ET_m) \qquad [3]$$

A quadratic fit to the data presented in Fig. 6 showed a curvilinear relationship [(% Y reduc.) = $1.4809^{**}\ ET_d - 0{,}0021\ ET_d^2 - 21.65$; $n = 46$, $R^2 = 0.95$]. The prediction, however, did not improve, since R^2 values for both linear and quadratic equations were the same, i.e. 0.95. In addition, the quadratic term was not significant. Therefore, a linear equation appeared to be adequate.

The relationship expressed in equation [3] led to a generalized form of the yield prediction model same as [1]. The slopes for different years of study ranged from 1.24 to 1.33 (Fig. 6). This fairly narrow range led us to infer that the aggregated slope of 1.29, with 95% predictive efficiency, can be adopted for the wheat variety studied, when ET_a timing is the best. Assuming this slope predictable, the yield reduction for any given season ET_a is predictable; if Y_m is known, then, Y_a is predictable.

To examine whether different timings of ET_d caused different yield reduction ratios, the timings of ET_d (the pattern of ET_d intensities experienced in a growth stage or time period) likely to cause large yield reductions were separated from those which do not reduce yield more than the minimum amount. For each spectrum of results, slope of the % yield reduction versus % ET deficit functional relationship was established (see Fig. 7). Zone 1 on Fig. 7, which is the same as Fig. 6, includes 26 data points (from all four years, 1971 through 1975) representing the yield reduction ratios of 0.2 to 0.7. The slope of this function was 0.90. The ET_d sequences resulting in ratio $\leqslant$ 0.7 (see ratios in zone 1 shown in Fig. 7) were considered to represent the "optimal" timing of ET_d. The optimal ET_d timing refers to the timing of ET_d intensities

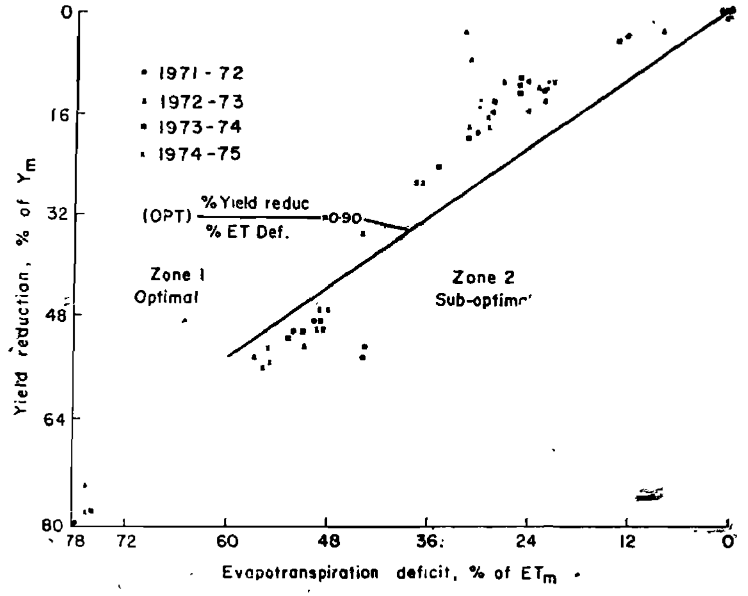


Fig. 7—Yield reduction ratios in relation to different timings of evapotranspiration deficit occurrences in the life cycle of wheat crop.

($ET_d/ET_m \times 100$) which resulted in essentially minimal yield reduction (17% below Y_m in this case, see Table 12 which summarizes required data from Figs 5, 6, and 8) for the total seasonal ET_d. Our earlier observations are that maximum profit [dY/dW = input (including application cost)/output price ratio; W denoted water] was obtained at about 82 to 90% of yield maximizing level of irrigation (i.e. where some slight water deficit is incurred). Whereas maximum efficiency of water use often occurred at irrigation level still lower than maximum profit point. These indicate that our attempt to designate ET_d timing which caused about 17% yield reduction from Y_m (Table 12) as "optimal" seems reasonable.

The slope of the relationship developed for points in respect of the ET_d timings producing wider ratios of 1.0 to 1.2, zone 2, was 0.94. The ET_d timings producing results in this zone was denoted as "suboptimal" timing of ET_d, which brought about 51 to 78% reduction in yield below Y_m (Table 12). In situations where the crop seems to have distinctly different growth stage sensitivities and irrigation schedules with respect to growth stages are suboptimal, stage-wise sensitivity factors would be required for yield predictions. The relationship remains as before but the slope (b) in this case would be $\geqslant$k, and the yield prediction model would assume the form :

$$\hat{Y}_a = \frac{Y_m \left(ET_m - \sum_{i=1}^{n} b_i \, ET_{di}\right)}{ET_m} \quad \ldots. \quad [4]$$

In equation [4], b_i's, i = 1, . . ., n, are sensitivity factors (slopes) determined for each of various stages up to the ith stage, and ET_{di}'s, i = 1, . . ., n, are the anticipated ET deficits in each stage up to the ith stage.

The slopes of the relationships for the optimal and suboptimal ET_d timings did not differ statistically. Therefore, the ET_d timing which produced results in zone 1 did not differ from the timing producing the data in zone 2. This led to the conclusion that a low or high yield reduction ratio (% Y reduction/% ET_d) resulted due to low or high intensity of ET_d. This can be seen from strictly a linear relationship between the % yield reduction and % ET_d over the entire range of results with prediction efficiency up to 95%.

The yield reduction ratios are inverse reflection of water use efficiency (yield/ET). A linear regression analysis of yield reduction ratios on water use efficiency resulted in a negative slope of 28.5 kg of wheat grain/ha-cm of ET, which refers to a fall in water use efficiency per unit change in the ratio. As this ratio becomes larger, the loss in yield due to an ET_d tends to increase.

An ET_d in a preceding growth stage hardens the plants to withstand some higher degree of ET_d in subsequent growth stages. To examine this possibility in our case, occurrences of actual ET_d intensities were sequenced with respect to the vegetative stage, the booting/heading stage, and the period from flowering to grain formation. The ET_d intensities in the three stages were plotted in both Fig. 8a and 8b, except the five points out of 16 data points (there were 4 plots in code -1 in each year, therefore 16 points for all four years) representing the code -1 of the irrigation which were plotted in Fig. 8b only. It was done because in 5 of 16 plots with code -1 the ET_d intensities during the vegetative growth stage were the same as in plots representing the optimal yield reduction ratios 0.2 to 0.7 (see 15 cross-points in Fig. 8a and 20 cross-points in Fig. 8b). Low ratios were plotted as filled circles, and high ratios as crosses. A line was drawn to separate the scatters representing low ratios from those of high ratios, hence to roughly indicate the optimal and suboptimal ET_d sequences. Though the line drawn is arbitrary, it reasonably separated the optimal from suboptimal ET_d timings and served the purpose in view which was to indicate the effects of preconditioning the plants on their ET_d tolerance in subsequent growth stage.

It was observed that without prior ET_d in the vegetative stage (this condition prevailed in plot with code 1, as stated earlier), ET_d tolerance was almost zero in the booting-heading period (see Fig. 8a) and was 30% for the period from flowering to grain development. Fig. 8a shows that ET_d of the order of 10 to 18% (mean 15%, see Table 12) in the vegetative stage (see the scatter of filled circles most of them are falling in 10-18% range) conditioned the crop to tolerate 30 to 35% (mean 34%, Table 12) ET_d in the booting-heading stage. Similarly, Fig. 8b was drawn to verify whether the ET_d in the booting-heading stage hardened the crop to tolerate more ET_d in the period from flowering to grain formation. This figure (also Table 12) shows that as much as 39% ET_d could be tolerated by the wheat crop in its flowering to grain formation period.

Thus in accordance to the "critical growth stage" concept,

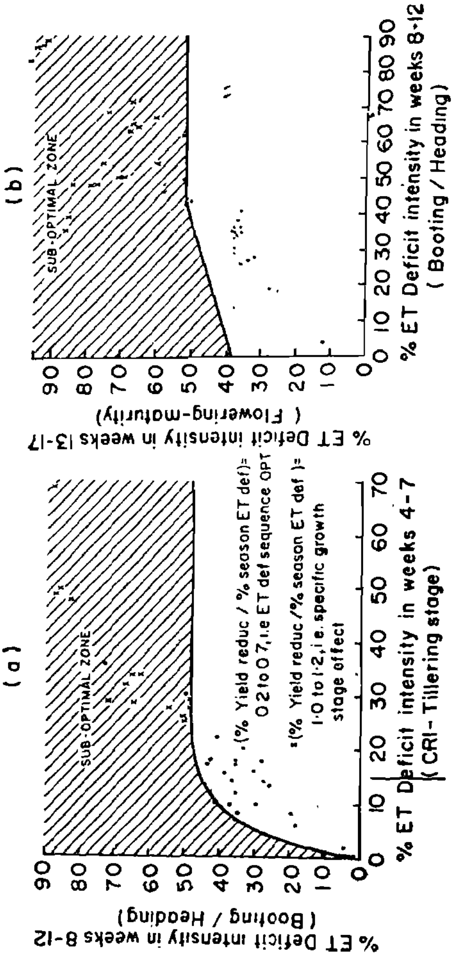


Fig. 8—Evapotranspiration deficit intensity in three growth stages of the wheat crop and conditioning effect of ET deficit on ET deficit tolerance in subsequent growth period.

the three growth periods of wheat crop could be rated, in order of decreasing sensitivity, as : booting/heading-flowering to grain development-vegetative stage. With this knowledge at hand, planning the strategy for the use of a limited water supply becomes a bit easier. To illustrate, a reference is made to an optimal plan developed by Singh (28) for the wheat variety Kalyansona grown at this site. His optimal plan is that which attempts to maximize yield per unit of water applied by successive deletions of the least contributive units of irrigation to yield. In this process of optimization, the anticipated ET_d is incurred in growth stage(s) or time periods the least sensitive to water stress. In the plan so optimized, irrigation required for the wheat crop to attain its Y_m to the order of 5,430 kg/ha was 84 cm, spread over seven irrigations given respectively 21, 40, 54, 68, 78, 90, and 100 days after planting.

With a small ET_d intensity of about 10%, the first irrigation 21 days after planting, i.e. at the crown root initiation (CRI) stage, got deleted from the irrigation schedule optimized to attain the Y_m of 5,430 kg/ha. This result led to the conclusion that the essentiality of the first irrigation at the CRI stage reported earlier (17) is applicable to an area where land is limited, water is unlimited, and the objective is to achieve Y_m by meeting ET_m requirement of the crop on each hectare of the farm.

With a 49% decrease in water application from that applied to Y_m, the irrigation schedule optimally programmed to cope with the water deficit tended to delete another irrigation 100 days after planting. This time period corresponded with the growth stage immediately after soft dough. Under an extreme water deficit intensity of 67%, irrigation 54 days after planting (late tillering stage) was deleted. Our unpublished data seem to suggest an alternative to deletion of irrigation 54 days after planting. It is based on marginal value product (MVP) determined for weekly irrigation water supply to wheat in a linear programming analysis. The MVP water was the highest for irrigation in the week coinciding with booting/heading, followed in order by that for the 4th week (active tillering begins) after planting and the week coinciding with the late tillering stage. At the beginning of the 4th week wheat plant begins to tiller. Spikelet differentiation also begins 20 to 25 days after planting (5). Moisture stress during this period will therefore reduce yield substantially. In wake of this fact irrigation 40 days after planting (optimally programmed in the optimal plan mentioned above) may be advanced and be given in the 4th week. In that case the next irrigation will be given 54 rather than 40 days after planting. Root growth following irrigation in the 4th week will extend the root zone to deeper layers permitting the plant to extract stored moisture from lower depths. The crop can remain unirrigated until the day 54 when the second irrigation becomes due. This little modification in the optimal programme of irrigation, without any increase in the amount and the number of irrigation, seems to have better practical applications.

Returning to impact of irrigation deletions on yield it may be emphasized that deletions timed in order of relative sensitivities of growth stages or periods brought about yield reductions smaller in magnitudes than the water deficit intensities relative to seasonal ET_m. The yield reductions from Y_m (5,430 kg/ha) to the order of only 6, 33, and 47% for the corresponding water deficit intensities of 10, 49, and 67% bear this fact out.

Timing water deficits in accordance to the critical growth stages may be important in its own right. However, in our case yields of wheat were sensitive to deficits at the "critical stage" (booting/heading) when the crop was not preconditioned to some moisture stress but were relatively insensitive when there was prior ET_d. This finding led to the conclusion that some of the anticipated seasonal ET_d should be allowed in the booting/heading stage. Thus if water is limited, irrigations should be so timed that the deficits are spread nearly evenly over the previous growth stages and the critical stage. These results therefore seem to override the much emphasized "critical growth stage" concept which suggests that no water deficit should be allowed in the sensitive stages of the crop growth.

SUMMARY

The actual ET deficit intensity, expressed as % of ET_m by which ET_a fell short in a time period, and its interrelations to yield responses were sequenced for three selected stages of growth : vegetative, booting/heading, and flowering to grain formation. The yield response to ET_d timings was expressed as "yield reduction ratio", i.e. % yield reduction (actual yield, Y_a, as % of the Y_m)/% seasonal ET_d. The ET_d sequences produced two ranges of "yield reduction ratios". Low ratios of 0.2 to 0.7 denoted the "optimal" timing of ET_d, since mean yield reduction was small–17%. Large ratios of 1.0 to 1.2 represented "suboptimal" timing of ET_d, which brought about 51 to 78% Y reduction. Within the range of optimal

ET_d sequence, Y reduction versus ET_d relation was linear. This relationship yielded a dimensionless slope to the order of 1.29, which being constant can be used for yield predictions by subtracting the yield reduction due to ET_d from ET_m. Without prior ET_d in the vegetative stage, wheat yields were sensitive to water deficit during the critical booting/heading period but were relatively insensitive when the plants were conditioned to some 15% moisture stress in the vegetative stage. This led to the conclusion that if water is limited, the deficits should be spread nearly evenly over the previous growth stages and the critical stage. Preconditioning the crop to some stress seems to reduce the impact of water stress in subsequent stages of growth.

Procedure for Optimizing Irrigation to Minimize Effects of Water Deficits on Crop Yield

The much emphasized concept of achieving maximum yield with nonlimiting soil water does not seem to have universal validity. There are instances where the maximum profit is obtained at about 82 to 90% of the maximum yield, whereas water-use efficiency maximizes at a still lower level (28). Thus in water scarcity areas, there is a need to optimize the number and depth of seasonal irrigations with a view to attain maximum production per unit application of water rather than maximum net profit per unit of area. This section deals with the procedure and methodology for optimizing the use of water in crop production under limited water supplies.

CROP ET FROM SOIL WATER STORAGE AT PLANTING AND WATER EXTRACTION PATTERN

Our experimental plots had received preplant irrigation each year in order to assure the crop season to begin with profile water at field capacity. In using this finding for predictive estimation of water extraction pattern, this water was treated as if it was derived from pre-season rainfall conserved in the soil, hereinafter termed as "unirrigated conditions".

The ET_m is the upper limit (for purposeful production) of crop-water-need; rainfall and profile storage together contribute to crop ET. Any gap between this contribution and the upper limit is what the irrigation has to meet. Therefore, the first requisite to optimizing irrigations is the knowledge of contribution to crop ET by rainfall and by initial profile water storage. This region does not experience rains in winter when wheat is grown. Therefore in CWS rainfall was not a factor. Contribution by stored soil water to crop ET is discussed as below :

Fig. 9 shows the importance of ET derived from stored soil water. In the first three weeks cumulative ETstor was equal to

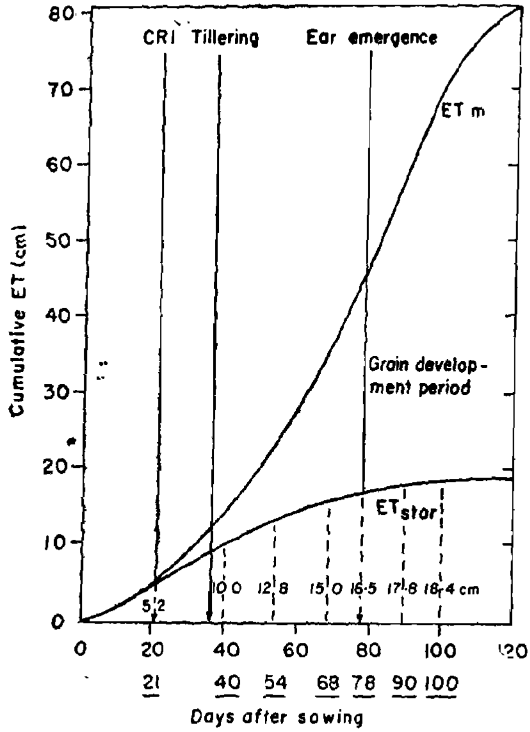


Fig. 9—Time functions of cumulative ET_m and ETstor averaged over 1971-75 to quantify the ET deficits at various stages of wheat crop, and the ET derived from stored soil water.

ET_m. The ET requirements early in the season, when the ground-cover was meagre (LAI = 0.3), might be due to more of soil evaporation than of crop use. ETstor continued to meet the crop water needs; the peak supply being in the 4th to 9th weeks when the tillering and part of the booting stage were completed. From the week 10th until maturity ETstor was only a fraction of a centimeter. The net ET_d to be met through irrigation during the 4th to 7th weeks, i.e. in the tillering stage, averaged 49%. From the booting stage until maturity the need for ET from irrigation was the greatest when ET_d varied from 82 to 94%.

To determine the ETstor and relate the root growth to uptake of soil water in storage at planting, a working hypothesis as given below was adopted. When soil depth, soil structure or other growing conditions are not impeding the root growth, and when soil water is at field capacity at planting time, the root proliferation is mostly determined by genetic character of the crop. Then, the time and intensity of ET deficit should be optimally distributed over the growing season and water use pattern should indicate the genetic potential (upper limit) of the crop to explore the soil profile and extract water therefrom.

To show the extraction of stored soil water as a characteristic of crop alone, the actual water taken up by the crop from particular soil layer in a growth stage or time period was expressed as percentage of field capacity at planting time. In this way Table 13 was developed which averages soil water extraction in four years. In this table column 2 gives the amount of water stored in particular soil layer at planting time, column 5 shows the portion(%) of stored moisture used between planting time and maturity, whereas other columns (6 to 11) each represent the amount of water taken up from each soil layer in a growth stage or a short time period within the season. Each row of figures adds up to the total seasonal water use from each soil layer.

The moisture depletion early in the season was mainly from 0–60 cm soil zone (Table 13). As the season advanced and the "centre of root activity" moved down into the profile, the lower layers largely met the ET requirement. Some water available for plant which under ET_m rate conditions remained in residual storage at maturity (see Table 14 col 9) was used by the crop in plot with ETstor notation.

In the ET process, soil moisture from all the depths was depleted to below the 15 atm percentage. It seems that in drier treatment the upward movement of water vapour along the temperature gradient (Fig. 10) set the condition for depletion of soil water below the 15 atm tension value.

Table 13 represents the genetic potential of wheat plants to take water from a layer in a growth stage or time period at the experimental site. In order to predict the water-use pattern in a growth stage or period at another site where this wheat variety is well adapted, what one required to do was to multiply each percentage figure by the soil water content in that layer at planting (assumed to be at field capacity) and then sum up the column. At the new site, the measurements required will be the soil depth, field capacity, and initial soil water content; also a knowledge of

Table 13. Actual water use (from plot with water code — 1.682, or 10.2 ha-cm of water) by the wheat crop from particular soil layer in a growth stage or days after planting of each growth stage expressed as percentage of field capacity (FC) at planting time, averaged over 4 years from 1971 through 1975.

Soil depth	Soil water content at			Season ET	Bulk density	Water use in different growth stages or days after planting of each growth stage						
	Planting (FC)	15 atm	Maturity			Season water use	Crown root initiation	Tillering	Boot	Heading	Grain development	Maturity
							21st day	49th day	70th day	86th day	110th day	120th day
1	2	3	4	5	6	7	8	9	10	11	12	13
	cm	cm	cm	cm	g/cm^3	%	%	%	%	%	%	%
0–30	4.9	1.4	0.2	4.7	1.58	96	46	35	3	8	4	0
30–60	4.5	1.5	0.4	4.1	1.50	91	41	26	8	9	7	0
60–90	4.8	1.5	0.7	4.1	1.52	85	7	31	15	16	11	5
90–120	5.6	1.7	0.9	4.7	1.61	84	7	17	24	18	11	7
0–120	19.8	6.1	2.2	17.6+		89						

+Available water in the 120-cm profile (FC-15 atm), cm	13.7
Evapotranspiration from use of water below 15 atm value (6.1–2.2), cm	3.9
Use of soil water, in vapour phase, by the crop from the reserve in the concretionary layer below the 120-cm profile, cm	1.4
Season total evapotranspiration, cm	19.0

soil physical conditions will be useful. In making predictions for a different soil only 90 cm deep, water depletion figures below that depth shall not be used, nor will the ET_a exceed the potential ET (at least for purposeful production).

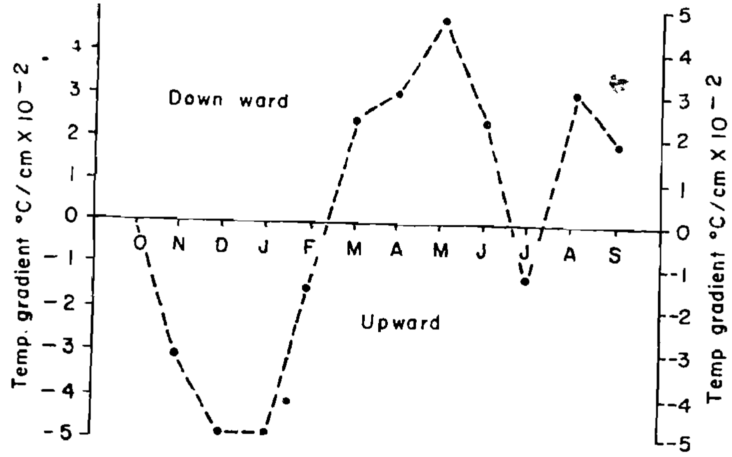


Fig. 10—Monthly variation in soil profile temperature gradient for the years from 1976 to 1978. (Source : Unpublished data of Dr. H.P. Singh, Soil Physicist at this Institute).

There are a few weaknesses in our estimate. First, the upper limit to soil water uptake by plants when expressed as a percentage of field capacity may not necessarily be constant for all soils. Secondly, if plants are established and there are proper growing conditions, water uptake will hardly be affected even when rooting depth is severely restricted by a limited soil depth. Nevertheless, the suggested procedure is believed to hold promise for providing clue to water planning in advance of the season.

CUMULATIVE ET_m

The ET_m/Ecor ratios rather than absolute ET_m values were used. Because at the optimal spacing and growing conditions the foliar growth becomes a varietal characteristic. Therefore the effect of dividing ET_m by Ecor is to normalize the climatic effect on crop ET which resulted in ratios representative of foliar growth alone. The ET_m, Ecor, and ET_m/Ecor ratios shown in Fig. 11 are based on four years average; each ET_m and ET_m/Ecor is the mean of eight observations. The horizontal line shows the time period and the circle in the centre indicates the mean ET_m for that time period; filled circle shows the mean Ecor for that period.

Four distinct ratios of ET_m/Ecor were evident : (i) a low ratio of 0.3 early in the season, when groundcover was little, was owing to direct evaporation, (ii) an increase in LAI from 0.3 to about 1.2 (mid-tillering stage, 4 to 6 weeks after sowing) resulted

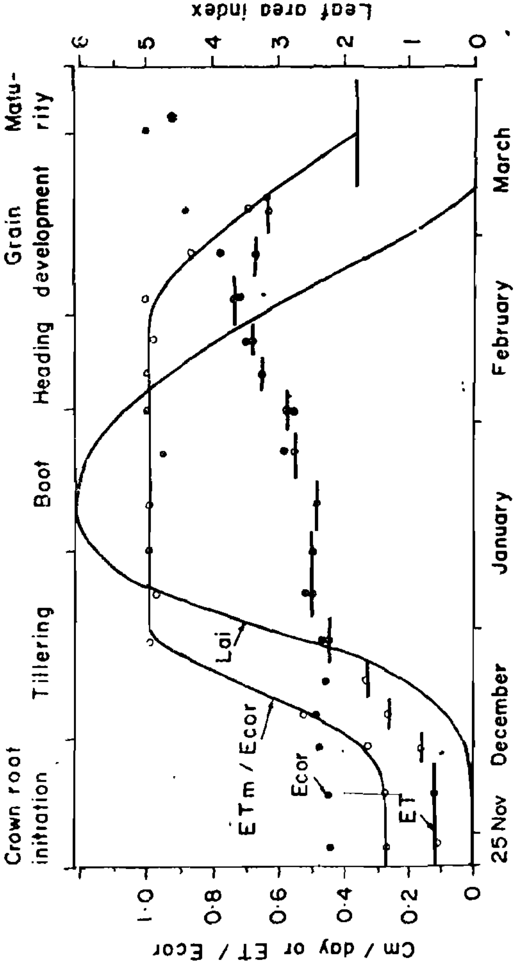


Fig. 11—ET_m, corrected evaporation from Class A pan (Ecor) and ET_m/Ecor ratios in relation to seasonal changes with time in leaf area index.

in a steep rise in the ratio from 0.4 to 0.9 (iii) a stationary state during the period from mid-tillering to completion of heading or early grain development stages (7th to 12th weeks, LAI >3), the ET_m exceeded the Ecor, and evaporation, whatever value it had, appeared to be a constant percentage of ET_m, (iv) during the period from grain development to maturity (LAI <3), the ET_m decreased, Ecor increased and the ratio declined. Thereafter, ET_m continued at a diminishing rate.

To use the ratios shown in Fig. 11 for predicting the ET_m at a planning site, only pan evaporation values are needed. It may not be necessary to correct for normal advection differences between sites since all the factors influencing Eo are integrated in a similar way by the crop and free water surfaces. Having predicted the ET_m from pan evaporation a curve showing cumulative ET_m can be drawn against time to obtain the ET_m for the season.

Optimization of Seasonal Irrigations

The measured ET_m and ETstor, averaged over four years, were combined (Fig. 9) in order to prepare an optimal plan of seasonal irrigations for wheat crop. An optimal plan of irrigations is that which fulfils ET_m with the optimum number and depth of seasonal irrigations (in light of the built-in unevenness of water distribution which characterises our irrigation method). Also, it provides for inevitable ET deficits due to limited water supply to coincide with stage(s) least sensitive to water stress. In optimization, each irrigation other than the last must refill the soil profile uniformly so as to assure ET_m at very point in the field. Uniformity of water application for meeting ET_m requirement of every spot in the field is important, otherwise some spots in the field would be left with insufficient water to satisfy ET_m, while from other spots the excess water would be lost to deep percolation. Another key requirement was that of the gross irrigation water depth in storage in the root zone immediately following an irrigation, only 70% could be utilized before the actual rate of ET_a falls below the ET_m rate. The next consideration was that the root zone storage would equal the root zone storage capacity (except the final irrigation). Thus, the minimum depth of irrigation required to refill the root zone would equal the root zone storage capacity, plus some deep percolation especially from those spots in the field where the water might be in excess of the quantity due to uncontrollable maldistribution of water, required to satisfy ET_m. As the root zone storage was considered equal to the root zone storage capacity, the deep percolation was assumed a function of this additional need of water owing to maldistribution in the flat land. Stewart et al. (36) have denoted this added requirement of water by a term dispersion of infiltration depth values around the mean depth, and have described the method for its determination. In our case, this quantity was assumed to equal 2 cm (proximate to reality for a level field) of irrigation water. This water depth was taken to equal the percolation, i.e. the amount of irrigation water that will seep down following an irrigation given to refill the root zone. No allowance to runoff (a nonexistent factor in this case) was given.

The goal set for optimization was to maximize yield per unit application of water. To achieve this goal the optimization tended to proceed in two steps. In step one, the number, date, and the depth of all seasonal irrigations were ascertained. Figure 9, which combines the 4-years mean ET_m and ETstor or ET_a for the season, shows that ET_m was 82 cm. ETstor was 19 cm. Thus the ET deficit remained to be met by irrigation was $(82-19) = 63$ cm. ETstor was equal to ET_m until 21st day, hence no irrigation was required prior to that day.On 21st day, the ETstor fell below the ET_m rate unless the crop was irrigated. At that time 5.2 cm of water would have been utilized in the ET process, so the soil water storage capacity to restore the field capacity was of the order 5.2 cm of water. Allowing 2 cm of water for deep percolation from some spots in the field where water might have been in excess due to uncontrollable maldistribution of water, the depth of the first irrigation (Irr-1) required was $(5.2 \text{ cm} + 2.0 \text{ cm}) = 7.2$ cm. Irr-1 then refilled the profile which means that 5.2 cm was stored in the root zone, and 2 cm percolated below the root zone. The ET_m rate was then maintained until 70% of profile storage from Irr-1 was utilized. Thus, ET from storage was 3.6 cm when the second irrigation must be applied. This brought us to the 40th day when, as shown in Fig. 9, ET_m exceeded ETstor by 3.6 cm. It may be noted that 1.6 cm of water from Irr-1 remained stored in the profile (residual storage) at this time.

On the 40th day, storage capacity was 8.4 cm, which represents 3.6 cm ET derived from storage in Irr-1, 4.8 cm ETstor since the 21st day, i e. 10 cm ETstor on the 40th day minus 5.2 cm ETstor on the 21st day= 4.8 cm. To store 8.4 cm of water in the root zone required 10.4 cm of irrigation. Following Irr-2 the profile contained irrigation water totalling 8.4 cm from Irr-2 plus 1.6 cm residual storage from Irr-1, or 10 cm of water. Seventy per cent of this 10 cm water could be utilized before Irr-3 was required.

This brought us to 54th day. At this time 3 cm of water was in residual storage (storages of Irr-1 + Irr-2). The ET from root zone storage in Irr-2 was 7 cm, plus 2.8 cm ETstor since the 40th day, thus water storage capacity was (7 cm + 2.8 cm) = 9.8 cm. To store 9.8 cm of water in the root zone, Irr-3 required was 11.8 cm. Of this, 2 cm was lost to deep percolation. Total irrigation water stored in the profile was then 9.8 cm + 3.0 cm residual storage from preceding two irrigations = 12.8 cm. Of this 70% or 9 cm was utilized until Irr-4 was required; residual storage of Irr-3 was 0.8 cm. This brought us to 68th day.

At this time the cumulative residual storage was 3.8 cm (from Irr-1 to Irr-3). ET_m between the 54th and 68th day was 11.2 cm (9.0 cm ET from Irr-3 in storage + 2.2 ETstor since the 54th day) hence water storage capacity on 68th day was 11.2 cm. To store 11.2 cm, Irr-4 applied 13.2 cm, of which 2 cm was lost to deep percolation. Irrigation water stored in the profile was then (11.2 cm + 3.8 cm) of water remaining in storage from preceding three irrigations = 15 cm of water. Of this 15 cm of profile storage, 70% or 10.5 cm was utilized in the ET process until Irr-5 was required. The residual storage in the root zone from Irr-4 was 0.7 cm. This brought us to the 78th day, when the next irrigation was required.

The ET_m for the period from the 68th to 78th day was 12 cm (10.5 cm ET derived from storage in Irr-4 + 1.5 cm ETstor since the 68th day). Thus profile capacity to store water was 12 cm. To refill the profile irrigation water required was 14 cm, of which 12 cm water was stored in the root zone. On the 78th day, 4.5 cm of water (storages from Irr-1 to Irr-4) was in residual storage. The total water stored in the profile was then (12.0 cm + 4.5 cm) = 16.5 cm. Of this, 70% or 11.6 cm was utilized until the next irrigation became due. The residual storage of Irr-5 was 0.4 cm. This brought us to the 90th day, when 6th irrigation was required.

At this time 4.9 cm water was in residual storage (storage from Irr-1 to Irr-5). ET_m between the 78th and 98th day was 12.9 cm (11.6 cm ET from storage in Irr-5 + 1.3 cm ETstor since the 78th day), thus water storage capacity was 12.9 cm. To store 12.9 cm, Irr-6 applied 14.9 cm water of which 12.9 cm water was stored in the root zone. The total profile water storage thus became (12.9 cm + 4.9 cm) = 17.8 cm, of which 70% or 12.5 cm was utilized before the final irrigation was required. However, the final irrigation might be given at any time the water storage capacity exceeded the needed depth of water with which to finish out the season at the ET_m rate.

The final irrigation (Irr-7) was required by the 100th day. On this day capacity to store water was 13.1 cm (12.5 cm ET from storage in Irr-6 + 0.6 cm ETstor since the 90th day), but only 8.8 cm of ET deficit potential remained to be met in the season (63 cm of the total ET deficit to be satisfied by irrigation, minus sums of ETs from Irr-1 through Irr-6). At this point it was assumed that only 70% of water stored in the root zone in Irr-7 (disregarding all residual storage from earlier irrigations) may be utilized before the actual ET rate will fall below the ET_m rate. However, no deep percolation will occur because the depth requirement for Irr-7 was below the water storage capacity, so though unevenly distributed, all of Irr-7 was stored (storage = irrigation). The 8.8 cm of water required to meet ET_m from Irr-7 was 70% of 12.6 cm of water, so this must have been the required irrigation depth.

Table 14. Optimal Irr plan to attain ET_m and Y_m of wheat, based on four years (1971-75) averages. Irr efficiency can be calculated from col 8 expressed as percentage of col 5.

Operation 1	Day No. 2	Storage capacity 3	Water infiltrated during Irr 4	Gross Irr 5	Percolation 6	Root zone storage 7	ET from storage 8	Residual storage 9
		cm						
Planting	0							
Irr-1	21	5.2	2	7.2	2	5.2	3.6	1.6
Irr-2	40	8.4	2	10.4	2	8.4	7.0	1.4
Irr-3	54	9.8	2	11.8	2	9.8	9.0	0.8
Irr-4	68	11.2	2	13.2	2	11.2	10.5	0.7
Irr-5	78	12.0	2	14.0	2	12.0	11.6	0.4
Irr-6	90	12.9	2	14.9	2	12.9	12.5	0.4
Irr-7 (Final Irr)	100	13.1	2	12.6	0	12.6	8.8	3.8
Total	120			84.1	12	72.1	63.0	9.1

Upon rearranging the computations in respect of seven seasonal irrigations, Table 14 finally emerged. In this table, the time sequence of ET deficits is reflected in column 8 labelled as ET derived from irrigation water stored in the root zone (column 7).

Table 15. Depth of seasonal irrigations (Irr) and ETs, contribution of ET value from an irrigation to yield of wheat crop, and yield per unit application of irrigation water.

Irrigation 1	Depth of Irr 2	ET from Irr 3	Contribution of ET to yield 4	Yield per unit of Irr 5
no.	cm	cm	kg/ha	kg/ha-cm
Irr-1	7.2	3.6	242	34
Irr-2	10.4	7.0	470	45
Irr-3	11.8	9.0	605	51
Irr-4	13.2	10.5	706	54
Irr-5	14.0	11.6	780	56
Irr-6	14.9	12.5	840	56
Irr-7	12.6	8.8	591	47
Total	84.1	63.0	4,234	

In column 8, the figure 63 cm is the sum of ETs derived from seven irrigations proposed in column 2.

In step two, optimization dealt with an aspect of yield maximization per unit of water applied. To illustrate, Table 15 was constructed which includes the first three columns from Table 14. Values shown in columns 4 and 5 were derived from data of Y_m and associated ET_m. The mean Y_m recorded was 5,430 kg/ha, with an ET_m value of 82 cm. The yield from unirrigated plot (ET stor plot) was 1,196 kg/ha with an ET value of 19 cm. Thus, yield from irrigation was (5,430 kg − 1,196 kg) = 4,234 kg/ha, and ETderived from seven seasonal irrigations was (82 cm − 19 cm) = 63 cm (see Table 14 col 8). Hence the gain in yield per cm of ET derived from irrigation was 4,234/63 = 67.2 kg/ha. Thus, each unit of irrigation led to some increment in ET which, in turn, was related to yield from irrigation at the rate of 67.2 kg/ha per cm of ET. At this rate the contribution from ET to yield shown in Table 15 (col 4) was calculated. Column 5 shows yield per unit application of irrigation proposed in column 2.

In a joint Indo-American Team report on "Efficient Water Use and Farm Management Study", prepared in January 1970 for Government of India, the crown root initiation stage in dwarf wheats has been ranked as the most sensitive to moisture stress. Our data in Table 15 (column 5) do not bear out this fact. Judged from contribution to final yield, irrigation in early period of growth as well as in time period after dough stage was the least efficient.

On the other hand, irrigations coinciding with the booting-heading and the period from flowering to early dough stage contributed substantially to grain yield.

The "critical period of growth" concept implies that no water deficit should be allowed in moisture-sensitive stage(s) of growth. Viewed in this context, our results suggest that if water application timing can be controlled, then Irr-1 will be deleted first when about 10% water deficit (Irr-1 is roughly 10% of total irrigation) is anticipated in the season. In anticipation of about 25% seasonal water deficits (water used for Irr-1+Irr-7 is roughly 25% of total irrigation), both Irr-1 and Irr-7 are subject to deletion from the irrigation schedule. Deletion of Irr-7 takes advantages of the fact that wheat plant osmoregulates and can reduce the effect of water deficit at later stages. Irr-2 shall be deleted next.

In incurring the water deficit, the crop yield begins to decline. Therefore the problem remains with the use of a limited water supply is to subject the crop to some water stress and at the same time reduce the losses in yield occurring due to incurring some water deficit. The number of irrigations correlates highly with yield (25). A simple way to resolve the yield-reduction problem is to keep the frequency (timing) of irrigations the same as optimally proposed in Table 14 (col 2). The depth of an irrigation will now reduce, which means that no irrigation will restore the root zone moisture to field capacity. The strategy which proposes to maintain the predetermined frequency of irrigation by keeping water depth to a level insufficient to restore the root zone moisture to field capacity can generally be termed as "under-irrigation" approach or "partial wetting of the root zone" approach. The under-irrigation approach has failed to give good yields in circumstances in which irrigation water or rainfall was not sufficient to bring, initially at planting, the root zone moisture close to field capacity. Thus, it is believed that this approach should preferably be restricted to wheat (also to other crops) planted in soils charged initially to field capacity by preplant irrigation or rainfall. The water deficits anticipated in the wheat growing season can be distributed, as indicated earlier, nearly evenly over seven irrigations proposed in Table 14 (col 2). Thus an under-irrigation approach which we propose seems to have important implications for planning strategies for efficient use of limited water supplies in countries with desert areas. The approach which requires the profile to field capacity at planting time and less than field capacity in successive irrigations needs field-testing.

SUMMARY

The system we developed satisfactorily approximated the maximum evapotranspiration as well as the yield, with the optimum number and depth of seasonal irrigations. Scheduling the occurrencess of unavoidable water deficits, due to limited water supplies, in growth stages or periods least sensitive to water stress was helpful in maximizing the yield per unit application of water. From these researched data and the data on soil and climate at a new workspot, evapotranspiration of wheat crop to be derived from irrigation alone is predictable at every level of water supply. The approach to optimization is believed to be applicable at every level of farm, project, or river basin water use planning, and generates information useful for both the farmer and the planner.

Allocation of Limited Water Supply to Different Crop Alternatives

The planning of water allocation involves decisions simultaneously on the crops or crops to be grown, the area to be allocated to each crop, the level of resources to be used in the production of each crop so as to maximize economic returns, and priorities to be assigned to the crop or crops when water supply falls short. Finally, the determination of relative profitability of an irrigation for a crop-mix at various stages of growth becomes crucial for water management decisions. This section deals with the allocations of four constant-rate water supplies to four crop alternatives viz., wheat (*Triticum aestivum* L.), sarson (*Brassica campestris* L. var. *dichotoma* Watt.), sunflower (*Helianthus annuus* L.), and safflower (*Carthamus tinctorius* L.).

The linear programming model defined the area irrigated from the given water supply, crop combination, area in each crop, input-mix, price sensitivity of the cropping plan, relative sensitivities of the growth stages to soil moisture stress, and the level of resources

Table 16. Area irrigated and the crop activities in the optimal solution for four water supplies.

Area irrigated from water	Area for each water supply (ha-cm) of 10.2	20.4	50.8	253.9
	ha			
20% constrained+	4.29	8.57	21.33	106.63
Unconstrained :				
Total	4.29	8.57	21.33	106.63
Activity-wise				
Wheat	1.61	3.21	7.99	39.99
Sarson	1.34	2.68	6.67	33.32
Safflower	1.34	2.68	6.67	33.32

+Activity-wise data were the same as for unconstrained water, except that for wheat where 37% land from activity shifted from Wopt to Wsubopt.

use. These are discussed under the two broad heads-optimum area irrigated and the optimum cropping plan.

OPTIMUM AREA IRRIGATED

Under our conditions characterized by loamy sand soil, plain plot surface, and the method of irrigation and operating system, the area irrigated tended to increase in direct proportion to the water supply (Table 16), the depth of preplant irrigation, and the number of weeks taken to carry out the planting. A 20% water deficit which was introduced in the supply at the end of growing season did not reduce the total area irrigated. This led to the conclusion that the area irrigated from the given water supply was fixed *ab initio* in proportion to the depth rate of preplant irrigation. However, a sizeable transfer of the area from the high to low-water-requiring crop activity did occur.

OPTIMUM CROPPING PLAN

The optimum cropping plan was independent of the water supplies (Table 16). This shows the neutrality of water availability input for its employment in maximizing returns irrespective of the choice of crops. Only the area under various crop activities increased as many times as increased the yield of water. Hence the optimal cropping plan for one selected level of water supply (e.g. 10.2 ha-cm) was discussed.

The total area irrigated from 10.2 ha-cm of water supply per week was 4.29 ha. Of this area, the wheat crop occupied 38% while each of sarson and safflower occupied 31% (Table 17). Sunflower was uneconomical. To enter into the optimal cropping plan of the farm sunflower at the activity level combining 8 cm water, 100 kg/ha N, and 60 cm row spacing required the shadow price (shadow price is the increase in the c_i necessary to bring that activity into solution. This was converted to a yield figure by dividing the shadow price by the price of the commodity) equivalent to 19.9 quintal/ha seed yield of sunflower. The yield level or equivalent price necessary for this crop to enter into the farm plan was four times the seed yield of 5.2 quintal/ha actually attained in the treatment plot which received only presowing irrigation. This proposition seems rather difficult to achieve. These results indicate that under the present input-output relationships sunflower will never compete for the limited water resources with wheat, sarson, and safflower.

Table 17. Optimal cropping plan, sensitivity of the plan, and adjusted water use plan for 10.2 ha-cm available water supply per week.

	Optimal Plan			Sensitivity of Optimal Plan			Adjusted Plan	
Crop	Area	Input mix	Yield	Shadow+ price in terms of seed yield	Crop	Input mix	Area	Yield
	ha		quintal/ha	kg/ha			ha	quintal/ha
Wheat	1.61	Wopt Nopt Dopt	47.2	121	Wheat	Wsubopt Nopt Dopt	2.68	47.2
Sarson	1.34	Wopt Nopt Dopt	9.6	51	Sarson	Wsubopt Nopt Dopt	2.68	9.6
Safflower	1.34	Unirr, Nopt Dopt	5.8	None			2.68	5.8

+Arrived at by dividing the required profitability figure of LP output by price of the commodity.

Table 18. Date and depth of irrigation as were in the activity matrix at Wopt referred to in the text.

Crop	Irrigation (cm) in weeks after planting																				
	1 23 Oct	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
								II		III								I			
Wheat				(6.4)	6.4			3.8		3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	
Sarson	7.6	(7.6)					3.8	I			II 3.8										
Safflower			7.6			(7.6)		III										II			I
Water use, ha-cm	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2

Numbers in brackets refer to activities included in LP matrix for utilizing surplus water. Roman numbers from low to high in a row indicate (in order of decreasing sensitivity) the "moisture-sensitive period" booting-heading, active tillering, and later tillering stage of wheat; flowering and grain development stage of sarson; and grain development, flowering, and branching and rosseting stage of safflower.

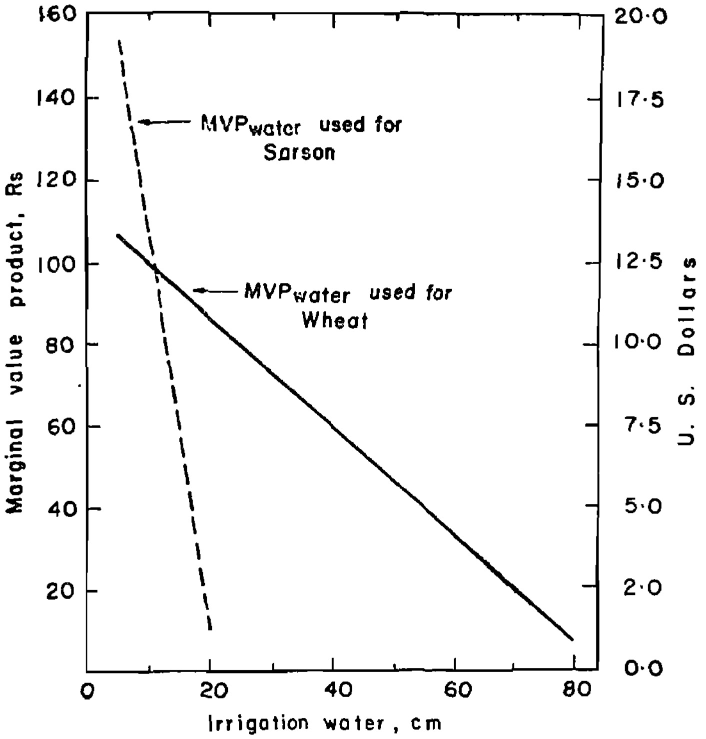


Fig. 12—Marginal value products for water allocated to one or the other of two crop alternatives.

Cropping Plan in Relation to a Constraint on Fertilize

Being a better choice under unirrigated conditions where response to fertilizer was limited, safflower ceased to be in the cropping plan when the fertilizer use was curtailed 50%. Since our major concern was the allocation of limited water supply to crops, the plan with respect to crop choice and the area allocated for a given water supply would nevertheless remain the same; however, safflower would not receive nitrogen. Without N, yield of safflower under restricted moisture would not be affected, so the return would.

Thus in the farm planning process, allocation of scarce resource (water) for the optimization of product-mix culminated into allocation of water to the competing crops. The area irrigated was proportional to the amount of available water supply. The choice of crops (in this case) was restricted to wheat, sarson, and safflower and was independent of the water supply. After planting, any amount of water deficit would not change the area irrigated but the level of treatment and the irrigation to a crop would depend upon the intensity and time of the deficit. The fertilizer shortage would not put limitation on planning the allocations of water to crops, except that the crop or crops having poor fertilizer use efficiency, owing to one or the other reasons, would not receive fertilizer.

SUMMARY

The area irrigated from 10.2 ha-cm per week water supply was 4.29 ha, which tended to increase as many times as increased the available water supply. Wheat, sarson, and safflower occupying respectively 38, 31, and 31% of irrigated area formed the optimal cropping plan whatever was the available water supply. Sunflower was uneconomical. After assigning 56 cm water, 150 kg/ha N, and 125 kg/ha seed to wheat; 17 cm water, 30 kg/ha N, and 40 cm row spacing to sarson; and a preplant irrigation, 50 kg/ha N, and 40 cm row spacing to safflower, this cropping plan showed the largest profit potential. A little change in resource position and use of the partial wetting method (initial moisture at field capacity and seasonal irrigations at one-half of the depth rate of preplant irrigation) allowed for full use of the available water supply in the growing season and doubled the area irrigated, the production, and the employment prospects. A 20% water deficit later in the season, or 50% less fertilizer availability, did not materially alter the plan or the acreage, but to cope with the scarcities the plan suggested a transfer of 37% of the total wheat area from the optimum to a suboptimum (29 cm) level of irrigation and withdrawal of fertilizer from safflower. However, if water deficit expectations shift to the earlier part of the season, it would pay to transfer water from wheat to sarson, but after 11 cm of seasonal water use wheat would have to be given priority.

New Irrigation Technology

Check basins are very inefficient on sandy soils, uneven surface. For this type of soil and topographic feature, sprinkler seems better. Sometimes high wind speed limits the use of sprinkler. Drip irrigation system is not affected by winds, nor is affected by uneven surface. It confines the irrigation water in close proximity to the root system. If managed properly, it maximizes production per unit application of scarce water and per unit use of better seeds, fertilizers, plant protection, and managements.

DRIP IRRIGATION VERSUS CONVENTIONAL IRRIGATIONS

The actual advantages of drip irrigation over conventional sprinkler or furrow irrigation have varied from a reduction in cabbage (*Brassica oleracea* L.) yield on a fine-textured soil at Mesa, Ariz, (2), an 18% gain in the yield of strawberries (*Fragaria* spp.) (41), and a better than 100% gain in the yield of vegetable crops using a saline soil and saline water in a desert area of Israel (7).

Application of fertilizers with the irrigation water applied by drippers and not with the water applied by other methods introduces unassessable fertilizer effects in addition to those of irrigation frequency and application efficiency. When Bernstein and Francois (1) maintained 100% water-application efficiency and shortened the irrigation interval, drip irrigation and conventional irrigation gave similar yields of pepper (*Capsicum annuum* L.). To achieve an efficiency of 100% in water application in the field is not possible. Neither is it possible to maintain the same irrigation frequencies with drip and furrow systems. Drip irrigation may not be beneficial when the irrigation interval is longer than 1 day and the soil is coarse, since its success depends on maintenance of high soil water content all time.

YIELD POTENTIAL

The patterns of yield accumulation of the four crops under the three irrigation methods are discussed earlier (see Fig. 1 in Singh and Singh, 1978). The benefits of drip irrigation were not the same for all crops (Table 19). Long gourd showed a significant 45 to 47% yield increase over sprinkler or furrow irrigated plots. The yield increase was associated with an increased number of fruits per plant and increased fruit weight. Yield increases due to drip irrigation on other crops were 21 to 38% with round gourd, 10 to 22% with watermelon, and practically nil with ridge gourd. The yields with drip irrigation were 20 to 32% higher than with daily sprinkler irrigation.

Table 19. Yields of long gourd, ridge gourd, round gourd, and watermelon under different methods of irrigation.

Crop	Furrow	Sprinkle/5 day	Sprinkle daily	Drip
1	2	3	4	5
	Metric tons/ha			
Ridge gourd	11a*	10a	—	12a
Long gourd	38a	39a	—	56b
Round gourd	30a	34b	31a	41c
Watermelon	67a	75c	69b	82d

*Means followed by the same letter in each row do not differ significantly at the 5% level by the L.S.D. test.

The results show that drip irrigation can increase the yield of some but not of all vegetable crops. Yield trends similar to those for ridge gourd were observed by Bucks et al. (2) for cabbage on a clay soil at Mesa, Ariz. With cabbage, drip irrigation at 12-day intervals and furrow irrigation gave similar yields. But dripper application equal to 105% of the consumptive-use rate applied at 3-day intervals reduced cabbage yield. It seems that frequent drip irrigation on a heavy soil interferes with aeration. In our study with trailing crops on a coarse-textured soil neither poor aeration, nor excessive evaporation from the fully covered soil surface could have been responsible for the small response of ridge gourd to drip irrigation. This crop continued to grow vegetatively without storing metabolites in fruits. Thus, crops which grow profusely at low water potentials will be less suited to drip irrigation.

The increase in yield of vegetable crops under drip irrigation over those under sprinkler or furrow irrigation on loamy sand soils in the desert area of Rajasthan and Israel (7) and the decrease in yields on the clay loam soils of Mesa, Ariz. (2) indicate that drip irrigation is better suited to coarse-textured than to fine-textured soils. Our results further show that total yields of watermelon and round gourd under SP-1 were 20 and 32% less than under drip irrigation. Much of the water was intercepted by the leaves and evaporated so that less was available to wet the soil. This problem could be overcome by applying more water. The maximum yield increase of 47% due to drip irrigation over sprinkler and furrow irrigation obtained in our study is much below the 100% increase reported by Israeli workers (7). We attribute this to the fact that under the climatic conditions at our location and on our soils the furrow irrigation method is also very good. The Israeli workers used a soil less well suited to furrow irrigation. The over-all performance of drip irrigation depends upon the usefulness of the methods to be replaced under a given set of growing conditions.

WATER-USE EFFICIENCY

Water-use efficiencies in terms of harvested yield (Table 19) per unit volume of water applied (Table 3) were 8.1, 5.4, and 11.0 kg/ha-m^3 for long gourd, round gourd and watermelon respectively. Water use efficiencies of these crops under sprinkler or furrow irrigation were only about one-half of the efficiencies achieved with drip irrigation. Thus, the maximum water-use efficiencies of these crops were achieved with drip irrigation while maintaining a high level of production. Water-use efficiencies of ridge gourd were lower, namely 1.3 to 1.7 kg/ha-m^3.

WATER ECONOMY AND USE OF SALINE WATER BY DRIP IRRIGATION

In arid regions water is scarce and efficient use of poor quality water by means of drip irrigation has become a necessity. Manufacturers claim savings of 50 to 90% in water by using drip irrigation. Bucks et al. (2) reported that evapotranspiration (ET) was about the same for several irrigation methods, but that drip irrigation required 22% less water than furrow irrigation. A report from Senegal shows an "estimated" 30% saving in water (10). Studies by Singh and Singh (29) showed that water applied by drip irrigation at a rate equal to the ET demand of the entire bed gave large yields. Where the rate of water supply by drip irrigation has been based on the ET demand of the wetted area only (2), a substantial water saving did occur but yields were similar to those on fields where other methods of water application were used. These studies seems to indicate that the evidence is inconclusive and does not afford a satisfactory basis for ascertaining the extent of water saving by drip irrigation.

In arid regions, the poor quality of water available for irrigation often poses a serious problem. Most supplies are salt laden. The use of saline water by sprinkler and furrow irrigation methods often results in low yields or crop failure.

WATER ECONOMY

The potato yield with Drip-ET$_{100}$ was 21 and 63% greater than with Drip-ET$_{75}$ and Drip-ET$_{50}$, respectively (Table 20). Thus irrigation at less than the ET rate reduced yield in about the same proportion as the amount of water used was decreased. A decrease in number of tubers was responsible for the decrease in yield in going from Drip-ET$_{100}$ to Drip-ET$_{75}$. However, a decrease in tuber size occurred by decreasing the rate of water application from 0.75 ET to 0.50 ET. About 35% of the loss in yield was attributable to the decrease in tuber size when irrigation by drip was reduced from 0.75 ET to 0.50 ET (Table 20). Yield with Drip-ET$_{50}$ was equal to Furr.ET$_{100}$ and Drip-ET$_{100}$ was 65% higher than Furr.ET$_{100}$. Thus,

Table 20. Yield and yield components of potatoes obtained during two growing seasons.

Irrigation method	Water use	Yield	Tubers	Wt/tuber
	cm	Mtons/ha	No./m^2	g
1972-1973				
Drip-ET$_{100}$	36.6	33.4c*	48b	98b
Drip-ET$_{75}$	27.4	27.6b	33a	100b
Drip-ET$_{50}$	18.3	20.5a	31a	87b
Drip-ET$_{100(s)}$	36.6	26.4b	36a	89b
Furr-ET$_{100}$	36.6	20.2a	34a	63a
1973-1974				
Drip-ET$_{100}$	28.6	27.5d	55c	59bc
Drip-ET$_{75}$	21.4	21.1c	40b	53b
Drip-ET$_{50}$	14.3	14.7a	42b	36a
Drip-ET$_{100(s)}$	28.6	14.4a	43b	39a
Furrow-ET$_{100}$	34.0	18.1b	32a	66c

*Means followed by the same letter in each column do not differ significantly at the 5% level by the L.S.D. test.

drip irrigation was capable of providing the same yield with "half" the quantity of water needed for furrow irrigation. The difference between Drip-ET$_{50}$ and Drip-ET$_{100}$ with respect to water-use efficiency was small, but the yield potential with Drip-ET$_{50}$ is much smaller than with Drip-ET$_{100}$. Hence, drip irrigation at a rate equal to the daily ET demand is the recommended practice.

USE OF POOR QUALITY WATER

The yield of potatoes irrigated by drip irrigation with water with a conductivity of 3,000μ mhos/cm was similar to Drip-ET$_{75}$, or 31% higher than achieved with furrow irrigation using good quality water. Using water with a conductivity of 10,000μ mohs/cm gave a yield of 14.4 metric tons/ha, which was equal to that with Drip-ET$_{50}$. Using water with a conductivity of 3,000μ mhos/cm gave a yield of 26.4 metric tons/ha. This suggests that it is possible to mix water with a high salt content with good quality water, in such proportion as to obtain a conductivity of about 3,000μ mhos/cm. This is an important observation because sweet water and salt-laden water are often obtained from wells located side by side.

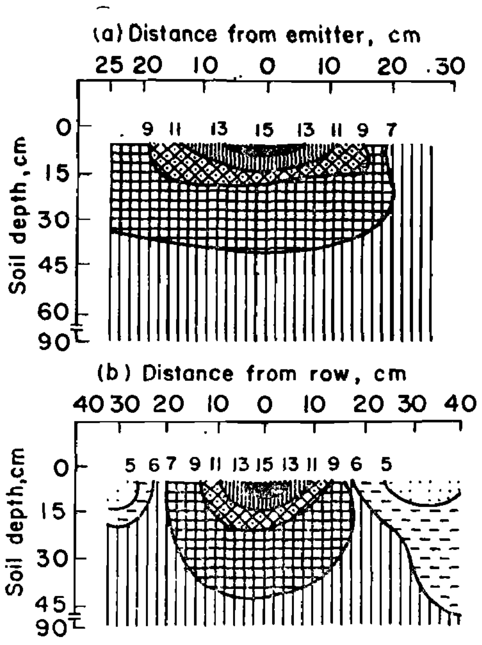
Water with a conductivity of 10,000μ mhos/cm reduced the yield of tomatoes by about 35% (Table 21). The yield of potatoes reduced by 91% compared with Drip-ET$_{100}$ (Table 20). The yield reduction in potatoes was due to a 28% decrease in number of tubers and a 51% decrease in tuber size. The decrease in yield of tomatoes was due to a 23% reduction in number of fruits only. Thus together with a decrease in yield, the quality of potatoes also deteriorated considerably with Drip-ET$_{100}$(s). But tomatoes grew well, maintaining produce quality similar to that achieved with Drip-ET$_{100}$.

Table 21. Yield of tomatoes under drip irrigation with good and poor quality water.

Irrigation method	Yield	Average tomatoes	Wt. of tomato
	Mtons/ha	No./picking	g/tomato
Drip-ET$_{100}$	59.4	91	34.4
Drip-ET$_{100(s)}$	43.9	74	31.5
Probability level	0.05	0.05	0.9

WATER CONTENT OF THE SOIL

Figures 13a and 13b show the distribution of water applied



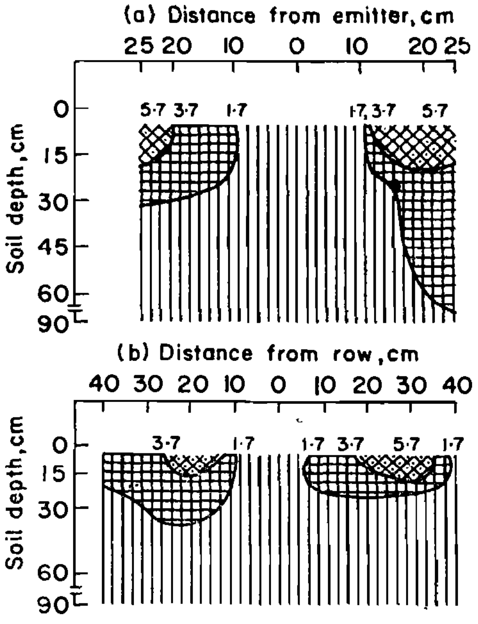


Fig. 13—Soil moisture content in percent (w/w) : (a) along the row, and (b) across the row of the tomato crop. Each value is the mean of three cores.

Fig. 14—Contour lines of conductivity of the soil extract in mmhos/cm, (a) along the row and (b) across rows.

by drip irrigation on the tomato plots. A distinct gradient in the water content existed from the point of application to the wetting front. The water content was 15% under the emitter, to a depth of 15 cm. It was about 7% at the midpoint between the emitters at the point 20 cm from the lateral. The water content was 3 to 4% towards the wetting front which was 40 cm from the lateral. The remainder of the soil surface was dry. The distribution of water is important for crop management. Generally, the yield of most field crops is not affected as long as the water supply remains above 60% of the available water on a loamy sand soil. A water content of 7%, which is well above 60% of the available water, in the upper 15 cm layer of soil midway between the emitters and 20 cm from the lateral, indicates the possibility of putting an additional plant between the emitters and manipulation of row spacing until the plant roots compete for the available water. In this way, the installation cost can be reduced in direct proportion to the number of plants supplied with water (31).

Figures 13a and 13b further show that a high water content extended to a depth of about 30 cm. Interplay between the ET demand of the crop and the small amount of water applied prevented the downward flow of water into the deeper soil layers. The water extracted immediately after irrigation came from the surface layers of soil, which were wetted during and shortly after irrigation. With furrow irrigation, the water content increased with soil depth (see Fig. 1c in Singh et al. 1978) but decreased with time. At the end of the irrigation interval the water content had decreased to about half of the initial water content of 8 to 12%. Considerable stress developed in the plants during an irrigation cycle. The water in the ridge crest (data not given) was always at or above field capacity where drip irrigation was used and water stress did not occur as frequently as with furrow irrigation.

SALINITY PROFILE

Salt accumulation after one season was highest in the surface 15 to 20 cm of soil midway between the emitters and towards the margin of the wetter band, i.e. 20 to 30 cm from the crop row (Fig. 14a and 14b). A salt-free zone existed below the emitter over the full depth of the soil profile. This study shows an accumulation of salts only in surface pockets. Goldberg et al. (7) reported accumulation of salts in surface pockets as well as in layers deep in the profile with a leached zone in between. Here the evaporative demand and plant absorption prevented the downward flow of water due to gravity and thus confined the salts to the surface layer.

The salts, removed from the zone of active roots accumulated in the surface soil away from the plants. Thus they would positionally be unavailable for causing injury to plants in all those regions where in-season rainfall does not occur. However, in areas experiencing rains during the growing season, the salts accumulated in the soil surface may be expected to be leached and distributed into the zone of active roots in amounts sufficient to injure plants (Fig. 14a and 14b). Obviously, this would impose a limit on the use of brackish water by the drip irrigation method. A package of special management practices must be developed for these conditions.

Moderately high salinity in the subsurface to very high salinity in the surface soil was observed at the midpoint between the emitters (Fig. 14a)· This condition imposes a limit on putting additional plants between the emitters. Further, the zone with a low salt concentration along the row was barely 15 to 20 cm wide. This limits the potential for planting paired rows in most crops. Hence, for installations of drip irrigation for use of saline water there should be a separate lateral for each row of plants and a dripper near each plant.

PLANTING CONFIGURATION IN RELATION TO WATER USE AND ECONOMICS OF DRIP IRRIGATION

The drip system was designed primarily to provide a separate lateral for each row and a separate emitter for each plant. The long length of the tubes and the large number of emitters required make drip irrigation costly for row crops. To resolve the cost problem, some workers (23, 42) have introduced a travelling or a mobile drip system. This system, however, adds another component to the total design.

In a system that requires a separate lateral for each row, spacing influences the cost. Thus, the optimum design tends toward maximizing spacing between rows. However, row spacing greater than optimum reduces plant population, and yield. If the plant population remains optimum and the number of drip laterals remains at a minimum, it becomes necessary to adjust the row and plant spacings such that one lateral controls two or more rows. In this case, the plants within row are usually spaced closer than normally recommended (26). A study conducted in Arizona (19) showed

Table 22. Effect of plant arrangements on crop yields.

Plant arrangement	Cabbage 1974-75	Cabbage 1975-76	Tomato 1974-75	Tomato 1975-76	Turnip 1974-75	Turnip 1975-76	Cauliflower 1975-76
	metric tons/ha						
Rectangular	7.6a*	35.5b	50.4b	68.4b	13.8b	19.5b	20.0b
Square	10.2a	33.2b	52.6b	73.1b	14.7b	20.3bc	23.8c
Hexagonal (single lateral)	8.3a	16.9a	32.7a	55.1a	7.3a	11.8a	13.2a
Hexagonal (double lateral)	—	17.8a	—	57.7a	—	10.6a	16.2a
Equilateral	13.8b	33.0b	39.8a	78.4b	13.2b	22.9c	26.0c

*Means followed by the same letter in each column do not differ significantly at the 5% level by Duncan's *multiple* range test.

that twin-row planting in potato (*Solanum tuberosum* L.) reduced the cost by 39% and reduced water use by 17%, but yield was 76% lesser than for rectangular planting.

In a recent study (29) it was observed that each lateral uniformly irrigated a 40 cm wide strip of soil. It was also observed that changing the conventional 60×25 cm rectangular planting geometry to a 25 cm square or equilateral planting geometry could result in a paired row planting, without changing the plant population. Under these conditions, one lateral could control each row pair. Also, changing to a 18.75 cm hexagonal planting geometry with a plant in the centre would result in a triple row planting with a lateral controlling all three rows, again without changing the plant population (Fig. 1).

YIELD AND PRODUCE QUALITY

Other than one exception the differences in crop yields between single and double row plantings were not significant (Table 22). The produce qualities were also similar. This was evident in the values of the yield components (Table 23) and in the marketable

Table 23. Produce quality as influenced by plant arrangements during 1975-76 cropping season. Data for HPA with double laterals are not given, for the goemetry is the same as in HFA with single lateral.

Quality component	Rectangular	Square	Hexagonal	Equilateral
Cabbage				
Wt./head, g (marketable)	644a*	707b	679ab	729b
Marketable wt, %	84	78	63	79
Cauliflower				
Wt./head, g	491b	529bc	378a	567c
Marketable wt. %	77	75	58	75
Turnip				
Wt./ball, g	313b	358c	253a	378c
Marketable wt, %	92	87	77	93
Tomato				
Mean no./picking	119ab	144bc	104a	162c
Wt./fruit, g	25a	21a	22a	20a

*Means followed by the same letter in each row do not differ significantly at the 5% level by the L.S.D. test.

weight percentage, which were the same in both single and double row plantings (Table 23).

However, the triple row configuration reduce yields of the four crops by 26 to 52% when compared with RPA. The quality of the produce was such that 37% heads of cabbage, 42% of cauliflower, and 23% balls of turnip were unmarketable. The quality of tomatoes was not affected; however, the number per picking was reduced by 13% (Table 23).

The data in (Table 22) further reveal a significant difference in yields between seasons. When management practices and the ET demands were the same (69.4 cm ET for 1974-75 and 70.6 cm for 1975-76) in both years, a significant difference in yields may have been due to the method of applying fertilizer. When all P and K were drilled in the row and the N fertilizer was applied in the drip irrigation system the yields of turnip, tomato, and cabbage were increased by 60, 65, and 200%, respectively, as compared with the same quantities of fertilizers not applied in the drip irrigation system and in the row. However, this trend needs further verification.

WATER USE

The total irrigation water applied (average of the 2 years) to turnip, cauliflower, cabbage, and tomato in the RPA configuration was 21, 24, 24, and 70 cm, respectively. The double and triple row configuration required, respectively, 50 and 75% less irrigation water (or irrigation equal to 34 and 17% of pan evaporation, respectively) than received the RPA plots. The water supply was restricted to a limited surface area and to the potentially active root zone of the crop (Fig. 15). The soil was dry below 105 cm in SPA and EPA, and below 90 cm in HPA plots but was above field capacity even up to lower 105-120 cm soil layer. This indicated that drainage below the root zone was prevented in the SPA and EPA but profile moisture conditions were conductive to deep drainage in the RPA plots.

The width of the moist soil surface (data not given) that could contribute to the evapotranspiration also varied with the treatments. Compared with the RPA treatment where 100% of the soil surface was moist, only 50% of the plot area was moist at the soil surface in the SPA and EPA treatments while only 25% of the plot area was moist at the soil surface in the HPA treatment.

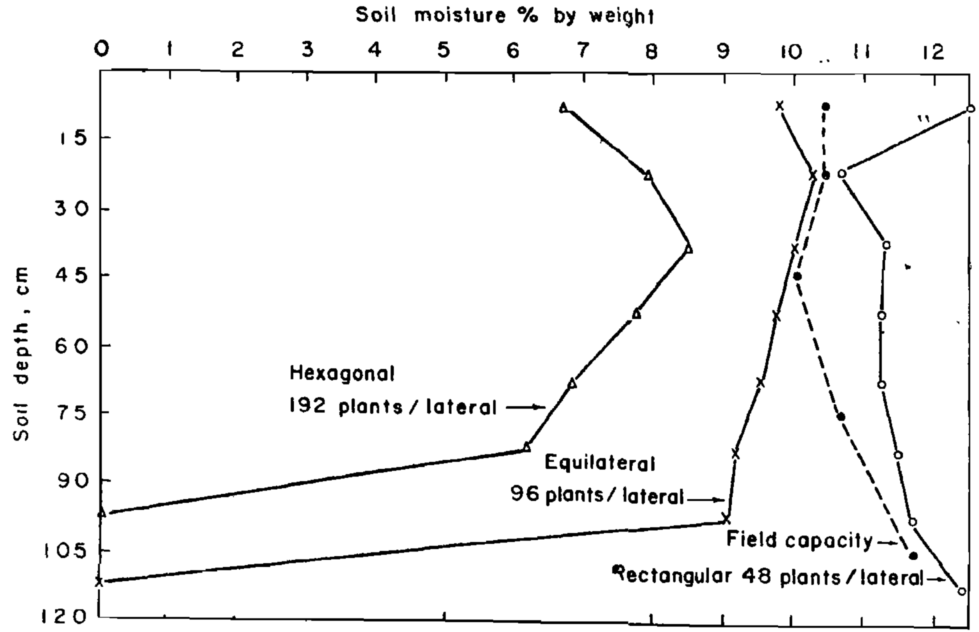


Fig. 15—Effect of rectangular, equilateral, and hexagonal planting geometries, respectively, having 48, 96, and 192 plants per lateral on water distribution in the root zone of tomato. The curves show moisture content in soil midway between emitters, 1 day after the final irrigation.

ECONOMY IN WATER USE, FERTILIZERS, AND INSTALLATION COST

The yield and quality of the produce were the same in both double and single row plantings. Thus, double row planting reduced cost and water use by 50% as compared with RPA treatment (single row planting). Further, the moist soil surface contributing to ET was restricted to 50% of the plot area. Therefore, there should have been more water available to each plant in SPA and EPA treatments due to : (i) volume of the soil where water uptake by the root system was the most efficient was wetted daily, (ii) 50% less soil surface area was available for direct evaporation, and (iii) drainage below the root zone was prevented.

In 1974-75, all the P and K and 78 kg N/ha (supplied by DAP) were distributed uniformly over the entire plot area. Then in double row configuration where water was restricted to half of the surface area of the plot, only 83% of the total N (half of 78 kg N as DAP+147 kg N/ha banded in the row are about 83% of the total 225 kg N/ha) and 50% of the total P and K could be in the moist soil. Nevertheless, the crop yields in double row configuration were comparable to single row planting RPA where 100% of the plot area was moist at the soil surface, thereby keeping full application of N, P, and K in the moist soil. Hence, the potential for fertilizer savings would also appear significant with double-row planting integrated into a high-frequency drip system. This possibility needs further study.

Triple-row planting reduced cost and water use by 75%. Hence an economical drip system is one which integrates the closer plantings and restricts the water application to the most efficient portion of the rooting volume only. In the HPA treatment only one-fourth of plot surface area was wetted, and the daily application of drippers kept the most efficient portion of the rooting volume so moist that the plants were never under water stress. However, yield and quality of produce on this HPA treatment did not bear this out. It caused excessive plant packing, introduced intense plant competition for space, and adversely affected the yield and quality of the produce.

The crop canopy characteristics modified the effect of plant competition on produce quality. In cabbage, cauliflower, and turnip, where foliar growth was confined to the plant-surface area, the competition was intense, which apparently reduced the quality. In tomato, some of the branches protruded outside the planted area and escaped interplant competition, therefore the quality was not adversely affected. Thus in tomato, HPA with two separate laterals per 2.40 m should reduce cost and water use by 50% and result in a yield potential of twice the present production (see Table 22) rate of 55 metric tons/ha.

SUMMARY

Drip irrigation increased the yield of long gourd by 45 to 47%, of round gourd by 21 to 38%, and of watermelon by 10 to 22% compared with sprinkler and furrow irrigation. All irrigation methods gave similar yields of ridge gourd. Thus, drip irrigation showed the potential to increase the yield of most, if not of all, vegetable crops. The water use efficiency with drip irrigation was nearly twice as high as with other methods of water application. Daily irrigation by sprinkling (SP-1) on watermelon and round gourd decreased yields from 20 to 32% when compared with drip irrigation. Hence, on loamy sand soils in hot arid regions, daily irrigation is advantageous when the water is applied by drip irrigation but probably not when the water is applied by sprinkler irrigation.

Drip irrigation at a rate lesser than the ET rate decreased the yield of potatoes compared with the rate equal to ET. To obtain identical yields, it required 50% less water than furrow irrigation. Saline water at 3,000μ mhos/cm applied by drip irrigation did not limit yields but at 10,000μ mhos/cm it reduced potato yields by 91% and tomato yields by 35%. The soil water content was about 15% beneath the emitter, 7% at a point 20 cm from the lateral, and 3 to 4% near the wetting front located 40 cm from the lateral. The wetted zone, extending 20 cm on either side of the lateral, could be used for twin-row configurations. Salts were concentrated in the surface 15 to 20 cm of soil at the midpoint between the emitters and towards the wetting front. Salts were not leached to lower soil horizons with the treatments used in these experiments.

The rectangular, both square and equilateral, and hexagonal planting geometries resulted in single, double, and triple row configurations and required four, two, and one drip lateral per 2.40 m plot width, respectively. The yield and quality of the produce were the same in both double and single row planting geometries. Thus, double row planting reduced cost and water use by 50%. The cost and water use were reduced 75% for the hexagonal planting geometry, but yields were 26 to 52% less than for the rectangular planting gemoetry; the produce quality was such that 37% heads of cabbage, 42% of cauliflower, and 23% of turnip balls were unmarketable. The quality of tomato, however, was not affected. Therefore, the hexagonal planting geometry in tomato with two separate laterals per 2.40 m should reduce cost and water use equal to that for double row planting and achieve a yield potential of twice the present production rate of 55 metric tons/ha.

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