EVALUATION OF WATER PRODUCTION FUNCTION AND OPTIMIZATION OF WATER FOR WINTER WHEAT (Triticum aestivum L.) UNDER DRIP IRRIGATION

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ABSTRACT

This paper presents the performance evaluation of seven selected crop water production functions (CWPF). The general objective of the study was to test the capability, suitability and validation of the different production function in predicting grain yield of winter wheat in tropical region of India were the crop growth period is 100 to 120 days. The seven production functions evaluated were linear, quadratic, cubic, power, Stewarts S_1, Stewarts S_1 and Singh *et al*. A field experiment was conducted during the 2012-13 and 2013-14 at Jain Hi-Tech Agri. Institute, Jain Irrigation Systems Ltd., Jalgaon located at Western scarcity zone of Maharashtra, India. The derived functions and those previously obtained by different workers were tested against the experimental data. There was a significant correlation of seasonal evapotranspiration with yield at different irrigation levels. The correlation, which was quite high for linear functions, was slightly greater for nonlinear functions. Among the all production functions, the non-linear function expressed by quadratic and cubic form for grain yield performed well and thus found to represent the data well as compared with linear production function. The test statistic of quadratic production function in 2012-13, 2013-14 and pooled basis were highly significant. The explained total variation (R^2) in yield with crop ET was more with quadratic function i.e. 91.64%, 97.07% and 93.64% as compared to linear function. The predicted maximum grain yield of wheat was recorded with 427, 338 and 383 mm of crop evapotranspiration during 2012-13, 2013-14 and on pooled basis, respectively. The economic optima of level of irrigation that will maximize the net return under prevailing prices worked out to be 382.8 ha-mm with the resultant grain yield of 4693 kg ha^{-1}.

Keywords: Drip irrigation, Wheat, Water production function, Optimization of water.
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1 INTRODUCTION

Food security in the world is challenged by increasing food demand and threatened by declining water availability. Irrigation is an increasingly important practice for sustainable agriculture. Water demand has significantly increased over the last decades while available water resources are becoming increasingly scarce. This is mainly due to the combined effect of climate change, persistent drought and the increase of water demands related to increase in irrigated surfaces, urbanization and tourism recreational projects. In this context, improvement of water management in agriculture, which is the biggest water consumer, is necessary to enhance agricultural productivity in order to meet food demands of the growing population (Misra, 2014). Thus, the research into the water requirement in Western scarcity zone of Maharashtra were wheat is a major food crop with short growth period (100-120 days) and suitability of appropriate water production function models (WPFS) is very important because they can help to draft guidelines on the region's irrigation and to improve the wheat yield.

A WPFS i.e. functional relationship between the crop yield and water use is needed to make decisions on resource development and effective management of the available resources assumption that other agricultural technical and agricultural factors are consistent, reflecting the response of crop yield to water change (Wang and Sun, 2003). It is the most basic function to regulate deficit irrigation, and also an important basis for reasonable allocation of the water resources, to achieve the maximum crop yield by optimizing the irrigation system (Wang and Sun 2003, Duan et al. 2004). In a WPFS, water input can be either on a seasonal basis or on a critical growth period basis. The corresponding functions are named seasonal functions and dated water production functions, respectively. Seasonal production functions can be effectively used when sensitivity of crop growth periods to water stress is not a practical significance or when irrigation schedules are well identified to produce maximum attainable yield (Ym) at each level of water output. However, the sensitivity of the crop to water stress may differ significantly among growth periods and it may not be feasible for management to adjust irrigation schedules within the optimal range; the more complex growth stage function is required in developing decision models for allocation of water in irrigation command areas. Vaux and Pruitt (1983) appraised numerous approaches relating crop yield and water in terms of ETa, transpiration and applied water.

The empirical functions which relates yield directly to irrigation water (IRR), transfer of results to other sites and seasons is not feasible. This is because the water used by the crop comes not only from irrigation but also from precipitation and available soil water storage at planting. Sometimes the available soil water depletion may be as high as 50 to 60 percent of total crop ETa. Another problem in relating yield directly to irrigation is that this variable is influenced by management practices such as land development, design and operation of farm irrigation system, time and amount of irrigation as a consequence some part of it, may be lost as drainage or runoff or stored in the soil at harvest. Such difficulties are not encountered when ETa is used as a variable. Therefore, the amount of irrigation water is relative and the relationships for crop water production functions as proposed by Nagel (1974) were modified by replacing the amount of irrigation with ETa in the present study. Further once Y vs ETa functions are developed, they can be translated to Y vs IRR or Y vs FWA (Field Water Supply) functions.

Up to now, crop water production function has been intensively studied in the world. Singh et al., (1987), Blank (1975), Stewart and Musick (1981) established the additive model to describe the relationship between water and yield. In China, (Kang and Xiong, 1991) carried out the relevant researches on distinguishing methods for crop water deficit status and irrigation index. Tang (2009) discussed the water requirement law and characteristic of rice cultivated in aerobic soil with different water deficit levels in different growth periods, analyzed the change law of different water deficit periods and water deficit degrees with the yield, and calculated the water sensitive coefficient and water production function of the rice. The research of Sun and Rong (2004) showed that Jensen model could better reflect the relationship between water and yield of winter wheat. Sun (2005) analyzed the influence of drought on the yield in different periods, and calculated the water sensitive coefficients of wheat, corn and cotton in different growth periods by regression analysis method. Likewise, Henry et al., (2007) evaluated Jensen, Minhas et al. modified Stewart et al. and modified Bras and Corodova models and revealed that Jensen model over predicted relative yield of maize by 10%, the modified Bras and Cordova, Stewart et al., and Minhas et al. over predicted relative yield by 6, 15, and 18%, respectively. The performance of the Jensen and modified Bras–Cordova models were considered better compared to the Minhas et al. and modified Stewart et al. models.

In this study, the performance of seven crop water production function *viz.,* linear, quadratic, cubic, power, Stewart S_1, Stewart S_2 (FAO) and Singh *et al.* were evaluated. The aim of the study to test the capability, suitability and validation of the production function for grain yield production. The specific objectives were to test the applicability and accuracy of in predicting relative grain yield of wheat. Optimization of water and predicting maximum grain yield of wheat with different seasonal crop evapotranspiration at different drip irrigation levels (pan evaporation replenishment). The output of this study is expected to advance the understanding of the performance of the selected function and serve as a guide to selecting which crop water production function to use in predicting grain yield of wheat under drip irrigation.

2 MATERIALS AND METHODS

2.1 Location of field experimental site:

The location of the experiment for the study was Jain Hi-Tech Agri. Institute, Jain Irrigation Systems Ltd., Jalgaon located at Western scarcity zone of Maharashtra, India. The site is geographically situated at 21° 01' 52" N-Latitude, 75° 56' 38" E-Longitude and at an altitude of 292 m above mean sea level. Agro-climatologically the area is classified as Western Plateau and Hills Region of Maharashtra.

The soil was sandy clay loam texture in surface layer and sandy loam in the remaining lower layer, neutral in reaction and non-saline (Table 1). Mechanical analysis of the soil at different depths revealed sand percentage increased with increase in soil depth from 0-15 cm to 45-60 cm. The soil moisture retention capacity at field capacity and at permanent wilting point and bulk density of the experimental site were estimated at 0-15 cm, 15-30 cm, 30-45 cm and 45-60 cm soil depths by following the standard procedures (Dastane, 1967) and resultant data is presented in Table 1. The total plant available soil water i.e. the difference between field capacity and permanent wilting point from 0 to 60 cm soil depth amounted to 89.83 mm. Hydraulic conductivity of soil found to be moderate (1.34 to 2.50 cm h^{-1}) was estimated by Constant pressure head method (Singarao et al., 2005). Bulk density found to be slightly affect the root growth (1.475 g cm^{-3}).

2.2 Weather condition during crop growth period

The geographical area of Jalgaon comes under dry tropical and semi-arid region. Winter is generally milder at Jalgaon and temperature begins to rise from January and reach it peak by May. Weather data during crop growth periods were recorded at the meteorological observatory located at Research and Development (R&D) Farm Jain Irrigation Systems Ltd., Jalgaon Maharashtra.

Mean weekly maximum temperatures ranged from 28.79 ^{0}C to 33.53 ^{0}C and 28.64 ^{0}C to 33.63 ^{0}C, while mean weekly minimum temperatures varied from 14.73 ^{0}C to 20.50 ^{0}C and 12.53 ^{0}C to 19.54 ^{0}C during 2012-13 and 2013-14, respectively. The mean weekly maximum relative humidity during the crop growing period varied from 35.09 to 58.17% and 58.86 to 88.67% while mean weekly minimum temperatures varied from 9.56 to 27.09% and 9.27 to 38.66%. During both years of experiment, there was no rainfall during crop growing period. The mean bright sunshine hours per day varied from 7.5 to 9.0 and 7.5 to 9.17. The average wind speed varied from 4.64 to 8.14 km h^{-1} in 2012-13 and 3.67 to 7.33 km h^{-1} in 2013-14. With respect to pan evaporation, mean pan evaporation ranged from 4.07 to 6.71 mm day^{-1} and 3.44 to 4.72 mm day^{-1} in 2012-13 and 2013-14, respectively.

The monthly cumulative pan evaporation values during 2012-13 were more than the 2013-14. The seasonal pan evaporation during the crop period was 513 mm in 2012-13 and 406 mm 2013-14, respectively.

2.3 Description of experimental treatments

There were five irrigation levels involving four irrigation through drip (DI - 0.6, 0.8, 1.0 and 1.2 pan evaporation replenishment) and one control (SI- surface check basin irrigation at 1.0 IW:CPE ratio) as main treatments with four sub treatments nitrogen levels (N_0, N_{80}, N_{120} and N_{160}) through drip summing up to 20 treatment combinations. The experiment was laid out in a split plot design with four replications. Both the drip and surface irrigation treatment plots were separated by buffer channels of 1.0 m width to avoid seepage into the adjoining drip irrigated plots. The crop was sown on 6th November 2012 and on 1st November 2013 (*Rabi season*) at 22.5 cm apart, using “LOK-1” wheat variety (140 kg ha^{-1}). Inline dripper line laid out on the ground surface along the crop rows at 0.90 m apart with emitters spaced at 0.30 m apart delivering 4 L h^{-1}. The application rate was adjusted as per the treatments. Irrigation treatments were given based on pan evaporation reading recorded at meteorological sub-station located in R & D farm. Drip irrigation was scheduled every alternate days and N-fertigation scheduled once in a week up to 65 days.

2.4 Seasonal crop water production functions

The functional relationship between crop yield and water use is defined as crop water production function. Water input can be either on a seasonal basis or on a critical growth period basis. The corresponding functions are named as seasonal and dated water production functions (Yaron, 1971).

Knowledge of the relationship between crop production and water use would greatly contribute in:
Is to estimate production levels under different irrigation regimes,

- Planning of strategies for water supply at farm and project level.
- Evaluation of alternative cropping patterns in relation to the availability and utilisation of water resources.
- Economic analysis of irrigation projects, design and management criteria.
- Allocation of water for given cropping pattern among crop under conditions of water shortage.

The temporal distribution of irrigation water and randomly incidental precipitation interact with other soil characteristics to affect plant water status/stress and yield. If the moisture is not limiting maximum crop growth would presumably occur under the abundance of other factors essential for plant growth. Given an initial moisture or irrigation regime, crop response to water will depend on when water is applied again, how much is applied and how much time lapses in the growing season until next irrigation was made (Hexam and Heady, 1978). Thus the complex of responses might occur as shown in Fig 1. Initial water application at different levels at time ‘t_o’ alone might result in the response given by curve ‘C’ might result. If the name set of application were made at a lesser time ‘t_2’ only a slighter greater response than ‘A’ may result as shown by the curve ‘B’ may be realised. Likewise, if a third set of irrigation is given at time ‘t_3’ the further response curve ‘D’ may be realised.

The seasonal water production functions evaluated in this study for wheat are as follows.

$$Ya = a + b\,(ETa)$$
$$Ya = a + b\,(ETa) + c\,(ETa)^2$$
$$Ya = a + b\,(ETa) + c\,(ETa)^2 + d\,(ETa)^3$$
$$Ya = a\,(ETa)^b$$

In the above functions designed as linear, quadratic, cubic and power, the
Ya = Actual crop yield (seed yield/ total dry matter) in kg ha^{-1}

ETa = Seasonal actual evapotranspiration in mm
a = Y-axis intercept,
b, c and d = Regression coefficients indicating the magnitude of yield variation (kg ha^{-1}) per unit increase in ETa.

Stewart (1972) replaced ETa in the equation Ya = a + b (ETa) by seasonal relative evapotranspiration deficit (ETd) and proposed the following relationship,

$$\frac{\mathrm{Ya}}{\mathrm{Ym}} = \mathrm{a} + \mathrm{b}\,\frac{(\mathrm{ETm} - \mathrm{ETa})}{\mathrm{ETm}}$$

In which, Ya, a, b and ETa are as defined earlier, whereas ETm refers to maximum evapotranspiration associated with Ym i.e. Maximum yield. In this function, the ‘a’ reflects the Ym and ‘b’ indicates the decrease in yield linearly per unit increase in stress factor (i.e., ETd) and the above equation can be simplified to

$$\frac{\mathrm{Ya}}{\mathrm{Ym}} = \mathrm{a} + \mathrm{b}\,\frac{(\mathrm{ETd})}{(\mathrm{ETm})}$$

In which, ETd = seasonal evapotranspiration deficit (ETm – ETa)

A model using actual values of ETa and yield may not be transferable from one site to another or even from one season to next. The climates at different sites may results in different actual ETa values for the same amount of growth (Barrett and Skogerboe 1978, Vaux and Pruitt 1983). Conversely, similar ETa totals at different sites or in different seasons may result in different yields when other factors such as nutrients become limiting.

The above equation was later modified in to a dimensionless form to increase the scope of transferability. The dimensionless function (S_2) as reported by (Stewart et al., 1977) was of the following form.

$$1 - \frac{\mathrm{Ya}}{\mathrm{Ym}} = \mathrm{Ky}\,(1 - \frac{\mathrm{ETa}}{\mathrm{ETm}})$$

Where, Ky is the yield response sensitivity factor. Stewart et al. (1977) supposed that the ‘Ky’ value is a genetically reproducible characteristic of a crop variety; if it is true, it would be transferable to locations other than the experimental site. However, the results of various workers (Musick and Dusek 1971, Hargreaves 1975, Rahman et al., 1980/1981, Singh and Malik 1983) for relationship between crop yield and seasonal ETa showed better non-linear relations and the marginal physical product of ETa decreased after certain value. This prompted (Singh et al., 1987) to propose a non-linear function of the following form,

$$\mathrm{Ya} = \mathrm{a} + \mathrm{b}\,[1 - (1 - \mathrm{x})^2]$$

In which,
Ya, a and b are as defined earlier, and
x = Relative evapotranspiration i.e., ETa/ETm

Downey (1972) examined relative yield versus relative ETa relationships for 10 annual crops and noted that a single function to describe the yields was unsatisfactory due to wide range of possible yields for a given level of ETa. When ETd occurred during vegetative phase, crops had higher yields than and formed a separate function from those crops where the ETd occurred during the reproductive phase. He concluded that "the magnitude of the yield reduction was not a simple function of ETa; It depended on the severity of ETd and particularly on the physiological stage at which the ETd occurred". Therefore, using the S_2 model of Stewart's equation [(1-Ya/Ym) = Ky (1-ETa / ETm)] the growth stage yield sensitivity factors to ETd for different treatments i.e., for specific crop-growth sub-periods were calculated.

The crop production functions with and without considering water deficit as expressed by equation Ya = a + b (ETa) and Ya = a + b $[1 – (1 - x)^2]$ were tested for seed yield of wheat.

The regression constants and coefficients and other statistical parameters for testing different crop production functions both for seed yield and dry matter yield were estimated by regression analysis (Gomez and Gomez, 1984).

2.5 Optimization of water

The data used for developing water production function (linear, quadratic, cubic, power, Stewart S_1, Stewart S_2 (FAO) and Singh *et al.*) and the best fit quadratic function was utilized for working out the economically viable levels of actual evapotranspiration (ETa) for maximum return, as:

$$\mathrm{ET_{opt.}} = \frac{\mathrm{b_1} - \frac{P_{ET}}{P_Y}}{2\ \mathrm{b_2}} \ldots\ldots\ldots\ldots\ldots\ldots..\,(\text{Zhang and D. Pei, FAO})$$

Where, ET, Pw and P_Y, crop evapotranspiration, price of water and yield respectively.

3 RESULTS AND DISCUSSION

3.1 Seasonal crop water production function

The seasonal water production function presented in Figure 2 to 5 do not account for the timing of ETa deficit during the crop growing season i.e. optimal sequencing of ETd is assumed.

The seasonal water production function as expressed by linear, quadratic, third degree polynomial or cubic, power, Stewart S_1, Stewart S_2 (FAO) and Singh *et al.* performed well for the grain yield of wheat in both years as well as on pooled basis. The explained total variation in crop yield as indicated by values of the coefficient of determination (R^2) varied from 0.912 to 1.0 in 2012-13, 0.901 to 1.0 in 2013-14, 0.914 to 1.0 on pooled basis for grain yield. The variance ratio (F value) for testing R^2 were statistically significant at all the cases for grain yield in 2012-13, 2013-14 and on pooled basis. The production expressed by quadratic and cubic form had higher R^2 values 0.999 to 1.0 for grain yield in both the years and on pooled basis, the regression coefficients were highly significant (P = 0.01) as compared with linear production function which were having R^2 values 0.912, 0.901 and 0.914 respectively. Therefore it can be inferred that the non-linear function expressed by quadratic and cubic form for grain yield production performed well and thus found to represent the data well. Many studies indicated that the quadratic function is most appropriate for crop production functions (Barrett and Skogerboe 1978, Hexam and Heady 1978, Musick et al., 1976, Stewart et al., 1976, Watkins et al., 1998). On the other hand, (Neghassi et al., 1975, Singh et al., 1987) reported that linear form of production for wheat is more useful.

The response of grain yield of wheat to seasonal ETa expressed by linear, quadratic, cubic and power functions is shown in Fig. 2 to 5.

The Stewart S_1 and S_2 function may be expressed and written in the form of linear function. Thus R^2 and F value for Stewart coefficient linear function under grain yield was either significant. The R^2 values were 0.912, 0.901 and 0.909 in 2012-13 and 2013-14 and pooled data basis respectively.

The R^2 value for the function proposed by Singh *et al.* modifying the stress factor in Stewarts function assuming a non-linear relationship between grain yield versus seasonal ETa were either significant and had R^2, F and t-values statistically comparable higher to linear, Stewarts S_1 and Stewarts S_2 function in 2012-13 and on pooled basis respectively except in 2013-14.

3.2 Optimization of water

The relation between wheat grain yield (Y) under each level of crop evapotranspiration (ET) was established following linear and quadratic production function. The resultant function and test statistics are as follows.

$$\left.\begin{array}{l}
\text{Linear} \\
\quad Y = 3001.5 + 2.8456\ ET \\
\quad R^2 = 0.100 \quad SEy = 2102.7 \quad F = 0.333 \\
\text{Quadratic} \\
\quad Y = -20049 + 116.39\ ET - 0.1364\ ET^2 \\
\quad R^2 = 0.9164 \quad SEy = 5274.1 \quad F = 10.962
\end{array}\right\} \text{2012-13}$$

$$\left.\begin{array}{l}
\text{Linear} \\
\quad Y = 2380.2 + 4.7438\ ET \\
\quad R^2 = 0.1267 \quad SEy = 2401.4 \quad F = 0.435 \\
\text{Quadratic} \\
\quad Y = -32259 + 218.16\ ET - 0.3224\ ET^2 \\
\quad R^2 = 0.9707 \quad SEy = 4595.1 \quad F = 33.132
\end{array}\right\} \text{2013-14}$$

$$\left.\begin{array}{l}
\text{Linear} \\
\quad Y = 2695 + 3.6697\ ET \\
\quad R^2 = 0.1166 \quad SEy = 2216.8 \quad F = 0.396 \\
\text{Quadratic} \\
\quad Y = -24374 + 151.88\ ET - 0.1984\ ET^2 \\
\quad R^2 = 0.9364 \quad SEy = 5379.4 \quad F = 14.731
\end{array}\right\} \text{Pooled}$$

The test statistic (R^2 and F – value) of quadratic production function in 2012-13, 2013-14 and pooled basis were highly significant. The explained total variation (R^2) in yield was more with quadratic function as compared to linear function. The explained total variation (R^2) in grain yield with crop ET was 91.64%, 97.07% and 93.64% during 2012-13, 2013-14 and pooled basis, respectively. Likewise, the sign of intercept (a) and regression coefficient of linear (ET) and quadratic (ET^2) were alike in all the equation.

The yield – water production function did not emerge through the origin and the value of regression constant (intercept ‘a’) was negative in quadratic equation indicating that increase in grain yield at a diminishing rate with higher levels of crop ET. The positive linear coefficient for ‘ET’ term denoted that grain yield increased linearly from the addition of initial crop ET levels. On the other hand, the negative second power (quadratic) regression coefficient (ET^2) suggested that the increase in grain yield from each increment of crop ET diminished at higher levels.

The predicted maximum grain yield was 4780 Kg ha^{-1} in the 2012-13 with crop ET of 427 mm, 4647 Kg ha^{-1} in the 2013-14 with crop ET of 338 mm and 4693 Kg ha^{-1} on pooled basis with crop ET of 383 mm, respectively beyond which the yield decrease (Figure 6).

The ultimate objective of this type of analysis is to predict the water rate that will result in maximum profit. These levels were accomplished by solving the following equations:

$$2012-13:\ d_Y/d_{ET} = 116.39 - 0.2728ET = P_{ET}/P_Y$$
$$2013-14:\ d_Y/d_{ET} = 218.16 - 0.6448ET = P_{ET}/P_Y$$
$$\text{Pooled}\quad :\ d_Y/d_{ET} = 151.88 - 0.3968ET = P_{ET}/P_Y$$

Where, P_Y is the price kg^{-1} of grain yield (` 20.0 $kg^{-1}$ grain) and $P_{ET}$ is the unit price of water (` 1.0 ha-mm).

The economic optima of level of irrigation that will maximize the net return under prevailing prices considered above worked out to be 383 ha-mm with the resultant grain yield of 4693 kg ha^{-1} (Table 2). The optimum irrigation water level represents one point on the derived demand curve (Fig 6). Thus economic optimum levels of irrigation water under different appraised prices of output and input show that the optimum level of irrigation water was inversely related to increase in price of water (P_{ET}), whereas it (ET_{opt}) had a direct positive and relationship with the price of grain yield (Table 2). It indicate that an increase in cost of irrigation, keeping the prices of yield constant, require the use of less water to derive maximum profit. But if the prices of produce increase, greater amount of irrigation water can be used profitably. Similar trend were noted with net return and net return per rupee invested. The increase in price of water from 0.75 to 1.50 ha-mm under given price of the produce, say ` 15 kg ha^{-1}, is associated with only 0.1 ha-mm decreased in demand of applied water. This low decrease in demand was due partly to fixed level of all inputs other than water and high value of marginal physical product of water, and hence the price of water did not substantially affect the quantity of water demanded.

CONCLUSION

To use irrigation water efficiently in wheat production, knowledge about plant responses to evapotranspiration is essential. Most commonly used forms of production functions were evaluated and the non-linear function i.e. quadratic and cubic equation was found to be most appropriate for the grain yield of wheat was perform well and found to represent the data well in this study. The optimal levels of evapotranspiration were determined under the yield-maximizing strategy often used by farmers and the profit-maximizing strategy used by economists. The predicted maximum grain yield was 4780 kg ha^{-1} in the 2012-13 with crop ET of 427 mm, 4647 kg ha^{-1} in the 2013-14 with crop ET of 338 mm and 4693 kg ha^{-1} on pooled basis with crop ET of 383 mm, respectively beyond which the yield decrease. The economic optima of level of water that will maximize the net return under prevailing prices considered above worked out to be 382.8 ha-mm with the resultant grain yield of 4693 kg ha^{-1}. The results of this study provide useful information to farmers to make irrigation decisions for profit maximization and for resource conservation.

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Table 1. **Physical properties of soil in the experimental field**

S. No.	**Parameter**		**Depth of soil (cm)**				**References**
			0-15	**15-30**	**30-45**	**45-60**	
1.	Texture	Sand (%)	61	62	61	65	Bouyoucos hydrometer method (Piper, 1966)
		Silt (%)	18	18	24	24	
		Clay (%)	21	20	15	11	
		Texture name	SCL	SL	SL	SL	
2.	Bulk density (g cm^{-3})		1.48	1.49	1.47	1.46	Core sampler method (Dastane, 1967)
3.	Hydraulic conductivity (cm h^{-1})		1.34	1.55	2.36	2.50	Constant pressure head method (Singarao et al., 2005)
4.	Moisture retention at field capacity (0.1 bar)		24.8	23.7	21.3	18.4	SPAW 6.02.75 (Saxton and Rawls 2006)
5.	Moisture retention at Permanent wilting point (15 bar)		14.3	13.8	10.9	8.6	SPAW 6.02.75 (Saxton and Rawls 2006)
6.	Available soil moisture (mm)		23.31	22.12	22.93	21.46	

Table 2. Economic return of wheat at optimum levels of irrigation water under different appraised prices.

Price of water (`/ha-mm)	**Price of produce (` kg^{-1})**	**Price ratio (Pr = P_{ET}/Py)**	**Optimum water (ha-mm)**	**Yield (kg ha^{-1})**	**Total returns (` ha^{-1})**	**Cost of water (` ha^{-1})**	**Cost of cultivation* (` ha^{-1})**	**Net returns (` ha^{-1})**	**Net returns / ` invested**
0.75	15	0.050	382.6	4693	70,395	287.0	23,699	46,409	1.93
	20	0.038	382.7	4693	93,860	287.0	23,699	69,874	2.91
	25	0.030	382.7	4693	1,17,325	287.0	23,699	93,339	3.89
	30	0.025	382.7	4693	1,40,790	287.0	23,699	1,16,804	4.87
1.0	15	0.07	382.6	4693	70,395	382.6	23,699	46,313	1.92
	20	0.05	382.6	4693	93,860	382.6	23,699	69,778	2.90
	25	0.04	382.7	4693	1,17,325	382.7	23,699	93,243	3.87
	30	0.03	382.7	4693	1,40,790	382.7	23,699	1,16,708	4.85
1.25	15	0.08	382.6	4693	70,395	478.2	23,699	46,218	1.91
	20	0.06	382.6	4693	93,860	478.3	23,699	69,683	2.88
	25	0.05	382.6	4693	1,17,325	478.3	23,699	93,148	3.85
	30	0.04	382.7	4693	1,40,790	478.3	23,699	1,16,613	4.82
1.5	15	0.10	382.5	4693	70,395	573.8	23,699	46,122	1.90
	20	0.08	382.6	4693	93,860	573.9	23,699	69,587	2.87
	25	0.06	382.6	4693	1,17,325	573.9	23,699	93,052	3.83
	30	0.05	382.6	4693	1,40,790	574.0	23,699	1,16,517	4.80

*Cost of cultivation excluding cost of water and fertilizer (Urea).

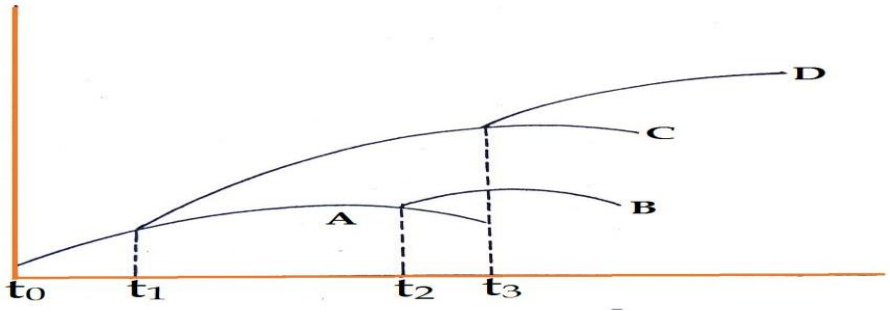
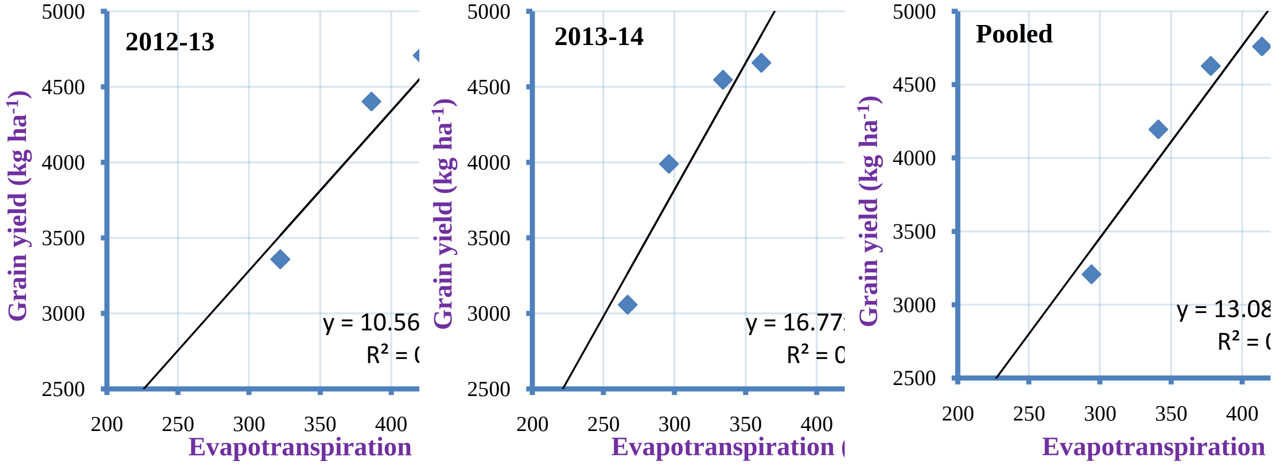


Figure 1. Dynamic of crop response to time and quantity of irrigation.

Linear Equation



Quadratic Equation

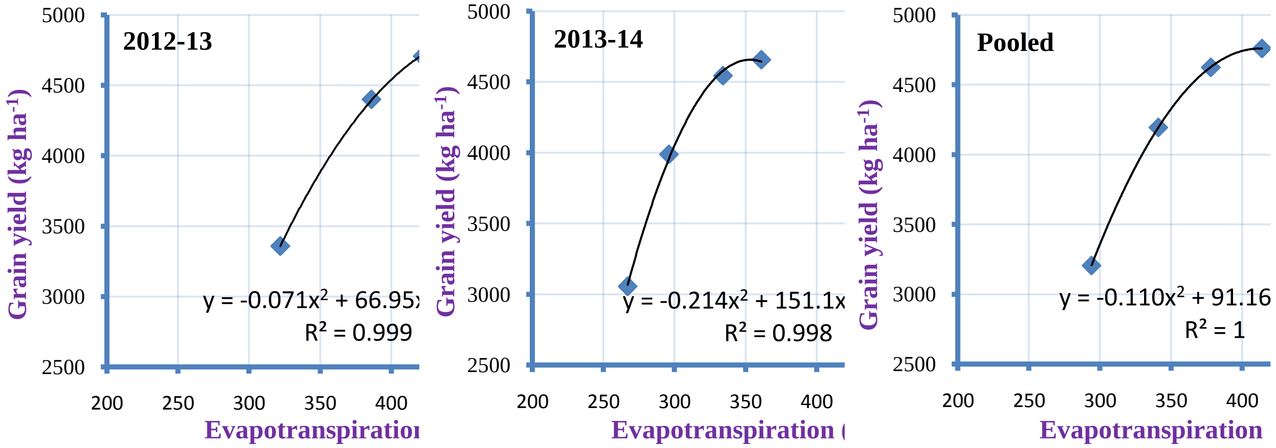
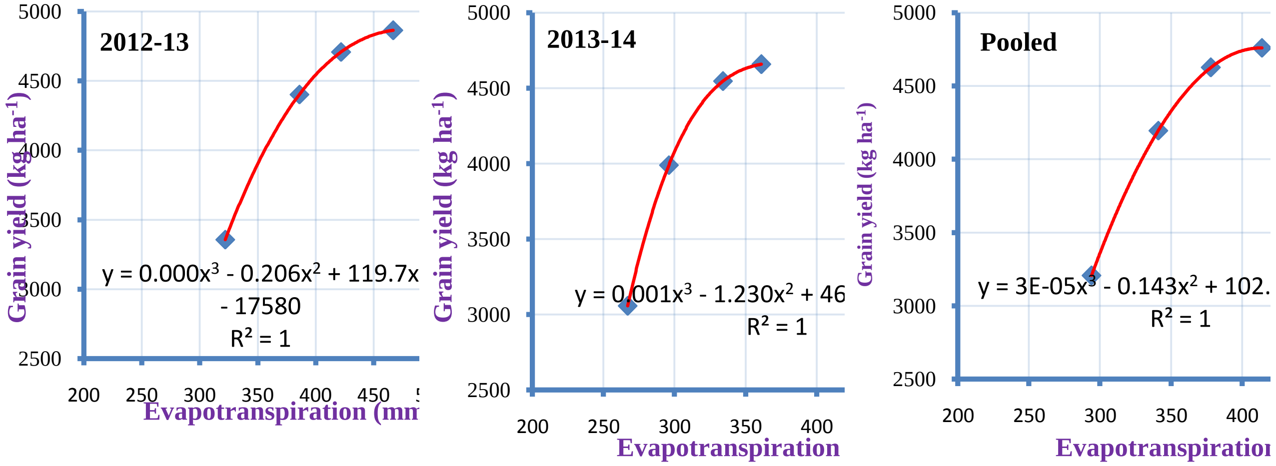


Figure 2. Prediction of grain yield response of wheat to evapotranspiration based on linear and quadratic function

Cubic Equation



Power Equation

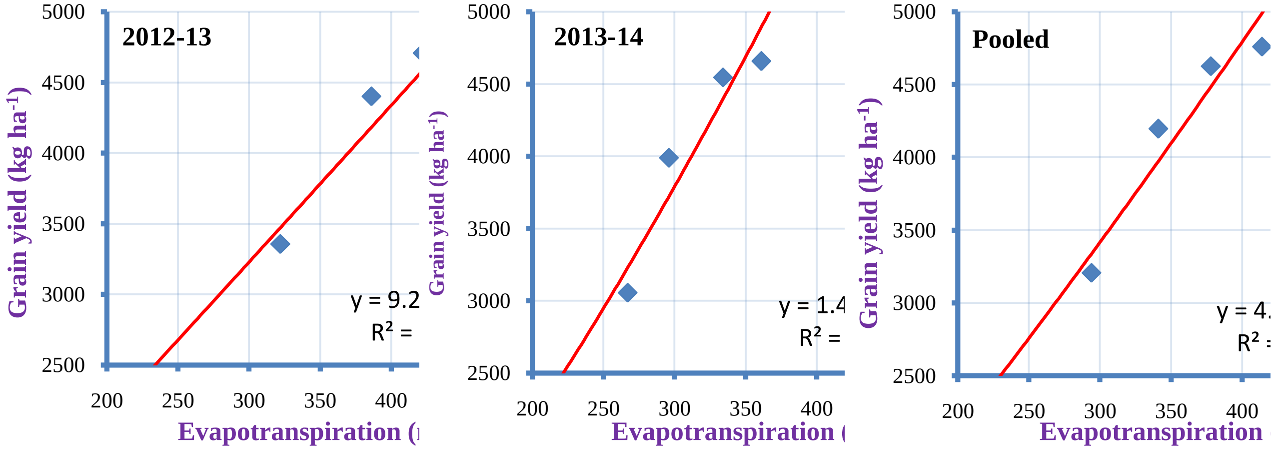
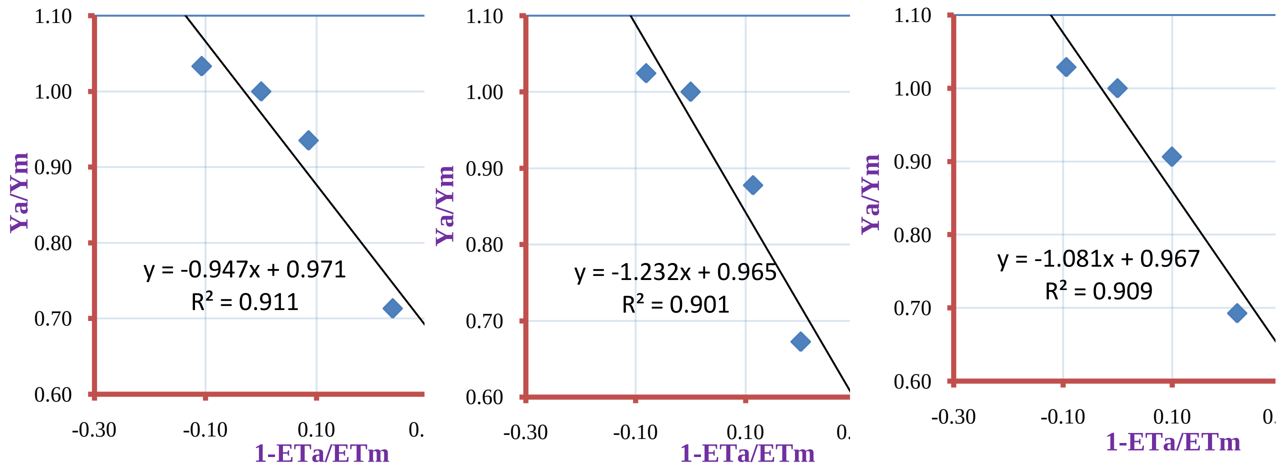


Figure 3. Prediction of grain yield response of wheat to evapotranspiration based on cubic and power equation



Stewart’s S_2 Equation

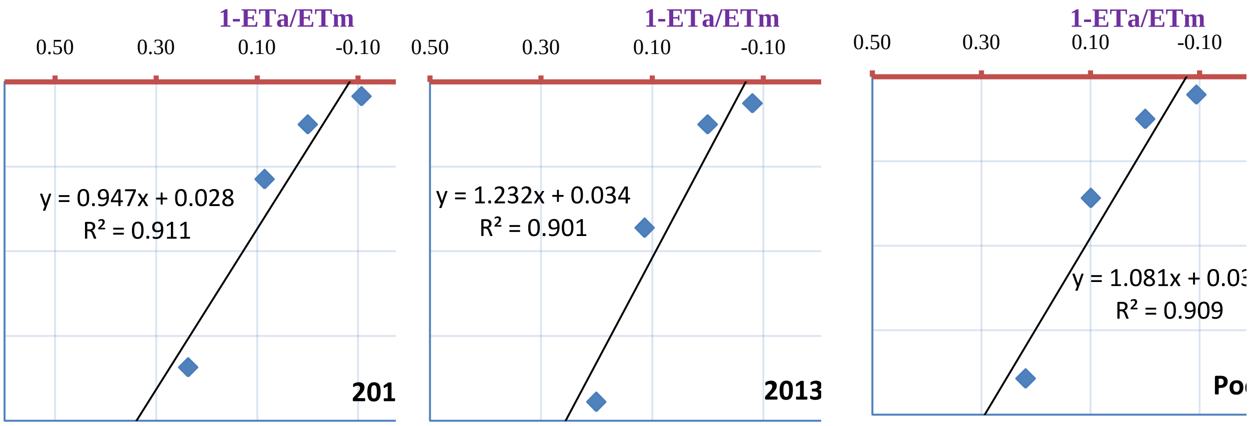


Figure 4. Variation of grain yield of wheat in relation to relative ETa deficit based on Stewart's S_1 and S_2 function

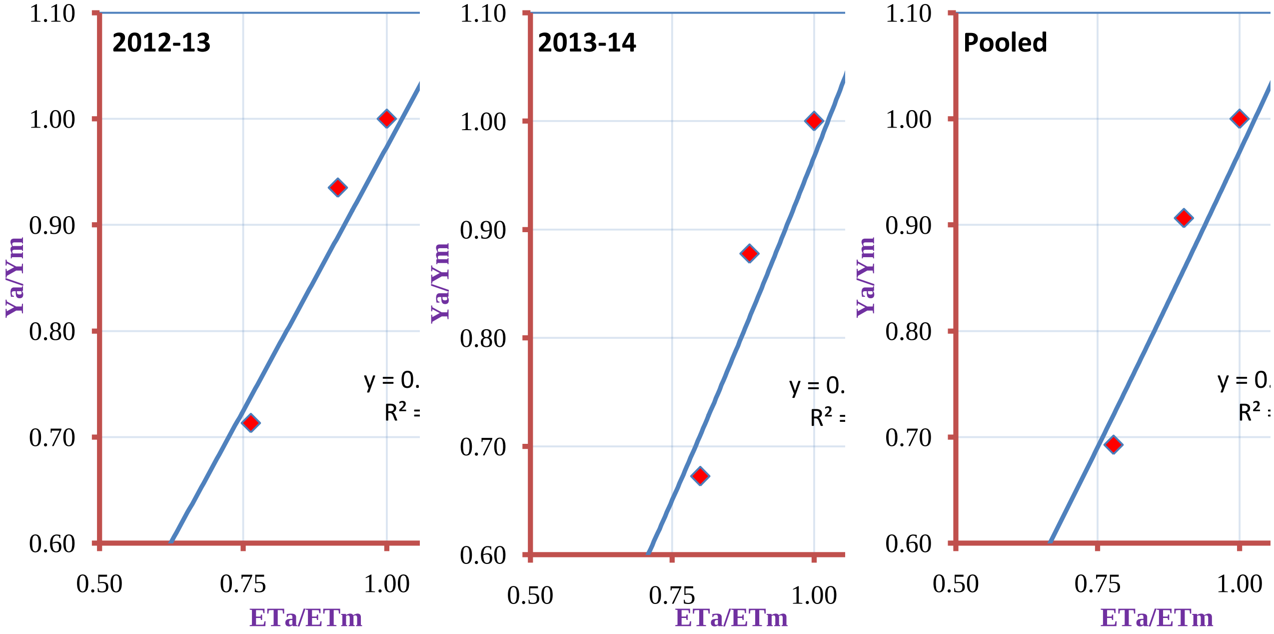
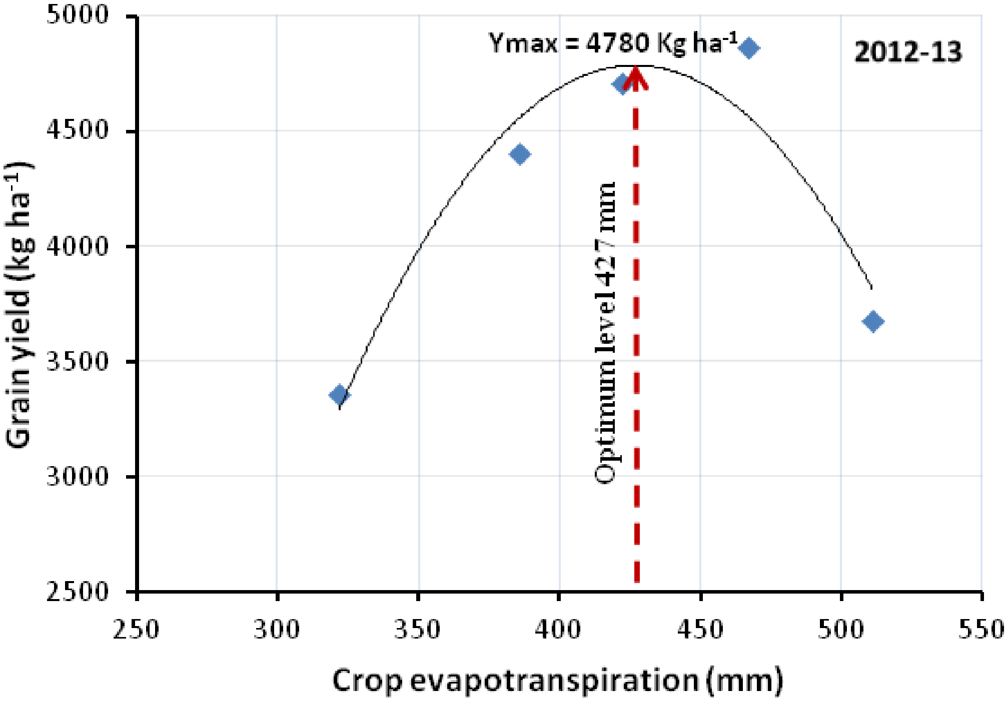


Figure 5. Variation of grain yield of wheat in relation to relative ETa deficit based on Singh *et al.* function



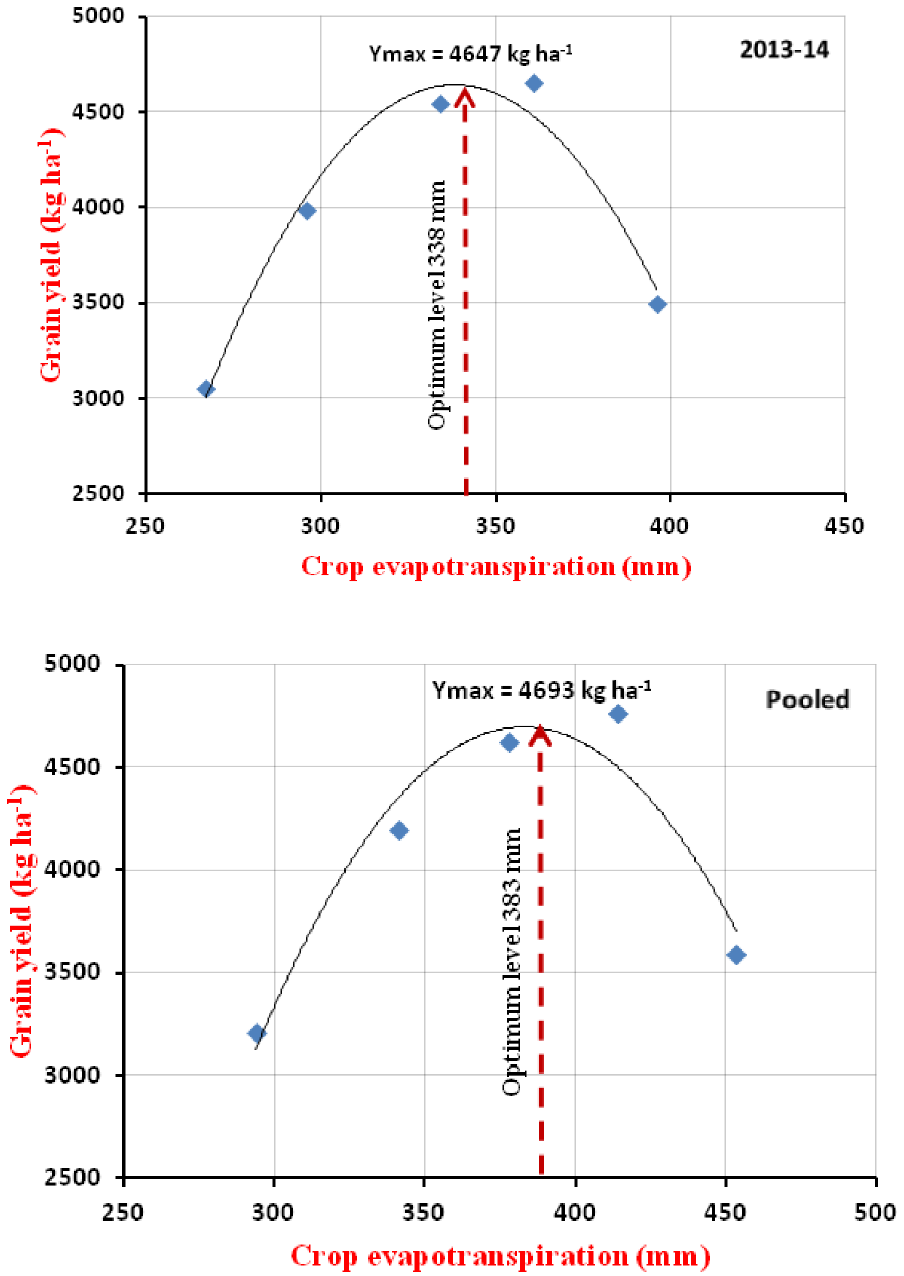


Figure 6. Predicted yield response of wheat to crop evapotranspiration.