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SENSOR BASED EFFICIENT SURFACE IRRIGATION SYSTEM FOR IMPROVING WATER PRODUCTIVITY USING EXPERIMENTAL AND MODELLING TECHNIQUES

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The role of hydraulic modeling and soil moisture sensors are very important for productivity enhancement and automation of surface irrigation systems by optimizing field dimensions and timely cutoff of inflow rate. Therefore, this modeling and experimental research was conducted at research site of University of Agriculture, Faisalabad-Pakistan. For this purpose, WinSRFR model and spark fun soil moisture sensor (SEN-13322) were used. After successful calibration of model and sensors, 19 treatments (01 conventional and 18 simulated) were installed in the field included, 2 level of inflow rate (Q_1=0.0025 and Q_2=0.0035 m^3/s), three sensor positions (55, 65 & 75%) along filed length and 3 levels of boarder width (B_1=6.4, B_2 =8.5 & B_s=10.7m) and for two wheat crop seasons (2016-17 and 2017-18). The results revealed that treatment T_{10} ($Q_2S_1B_1$) has high efficiency and uniformity i.e., application efficiency (AE) = 90%, min. distribution uniformity (DU_{min}) = 87% and distribution uniformity lower quarter (DU_{lq})=91, among other treatments. The values of wheat growth parameters were higher in all treatments of Q_2 compared to Q_1. The average minimum amount of water applied was found T_{10} (370mm) and achieved maximum water productivity of 14.13 kg/ha/mm compared to control treatment. It was concluded that the significant amount of water was saved along with higher crop yield by optimizing boarder width, cutoff time and inflow rate. It is recommended regional research should be conducted using hydraulic modeling and soil moisture sensors for improving forming output in surface irrigation.
Keywords: Soil moisture sensor, hydraulic modeling, application efficiency, distribution uniformity, WinSRFR model

INTRODUCTION

Water dearth has become fundamental problematic and challenging issue globally from last few decades. Its scarcity has also influenced on agricultural productivity and forced the scientists to think over the efficient use of available water resources (Wilhite and Pulwarty, 2017). Pakistan is a developing country and has also facing issues like water shortage due to industrialization, urbanization and increasing demand. The volume of water resources in Pakistan was 5600 m^3 per capita in 1950 but with the passage of time the volume of water resources has been decreased below 1000 m^3 per capita causing water deficit and it would be 50% added shortage by 2025 (IFPRI and IWMI, 2002). Therefore, efficient irrigation procedures are very crucial under such conditions to tackle the water deficit condition to fulfil the demands of agricultural products by utilizing limited available water resources and decreasing water losses (Qadir *et al.*, 2007).

In Pakistan, mostly farmers are irrigating crops by traditional methods i.e., flood or border irrigation because of higher management and operational cost of high efficiency irrigation system (HEIS). In traditional surface irrigation methods, movement of water is along the field length, thus flow as water sheet. This method is considered as a less efficient regarding water use and management, because water runs towards tail-end of the field. Efficiency of the surface irrigation system can be enhanced, if water is cutoff at suitable period, earlier it reaches at field tail end boundaries (Arnold *et al.*, 2015; Strelkoff *et al.*, 2009; Horst *et al.*, 2005). Appropriate limited strategy can reduce overflow from 17 to 22% in the heavy weight clay soils field areas (Bali *et al.* 2001). But it is critical to manage cutoff time. Whereas, well-managed and optimal design parameters in surface irrigation systems can enhance application efficiencies up to 80% Shakoor *et al.*, 2012). Recent researches in sugar industry revealed application efficiencies for single irrigation ranging from 20 to 85% enhancement and increased in seasonal efficiencies commonly range between 25 to 58% (Koech *et al.*, 2018). Normally, to apply cutoff strategy, farmer has to make many rounds to field to know when dose water reaches at a specific distance from tail-end, means cutoff irrigation based on field experience. Therefore, it is need of time to develop advance technologies for precise irrigation system which can improve yield by applying minimum quantity of water yet enhancing water productivity, with less operational and management cost. For this purpose, a typical surface irrigation system is equipped through soil moisture sensors which might be useful to supply miserable amount of water without over irrigation (Lo *et al.,* 2020).

Recently, new technical approaches have been introduced to determine and monitor soil moisture contents using the soil moisture monitoring sensors and can also be determined the how much of water required and to minimize the water losses from the plant and soil surface. Water use efficiency can be determined by different irrigation level of water with precisely irrigation plan scheduled (Koster, 2004; Seneviratne *et al.*, 2010; Teuling *et al.*, 2013). Soil moisture sensor monitoring irrigation approaches have capability and credibility to be quite proficient and yield great crop productivity. Design and management optimization can also be obtained using the simulation models to enhance the water application efficiency and crop productivity. They also can reduce the deep percolation and downstream end or tail end water run-off. This can be achieved through proper design factors including slope, width and field length, or through inadequate managing administrational practices which includes cutback rate, water inflow rate, cut-off location, and proper cut-off time. Improvement in water application efficiency results in saving of significant amount of water, high crop yield and less harm to the environment (Rockstrom and Falkenmark, 2000).

There are various hydrological models but two irrigation models have gained the most recognition and are being used as complete models including the zero-inertia Strelkoff or SRFR model (USDA, 1997) and the hydrodynamic Walker or SIRMOD model (Walker, 2001). Both models are relatively analogous in numerous techniques but they handle some of the computational features differently. WinSRFR is an advanced version of SRFR model which provides more computational options in comparison with SIRMOD model and it explains equations of mass and momentum conservation of general physics. Models are fixed with equations and empirical formulas to examine the infiltration rate and bed roughness characteristics of the field. Formulas are accompanied with coefficients of the specific site and suited with system inflow parameters and geometry of the field (Anwar and Ahmad, 2020).

So, keeping in view, the importance of hydrological modeling and soil moisture sensors, the present study was designed to apply both techniques to enhance crop water productivity in surface irrigation system. Moreover, Wi-Fi and computer communication network were equipped with conventional sensor based system for assessing actual interval of irrigation, and to automate irrigation system in Pakistan. Thus, the objectives of the research were: 1) to calibrate and simulate surface irrigation model for real time soil and inflow characteristics, 2) to test different scenarios on the basis of field dimensions, inflow rate and cutoff time using soil moisture sensors for optimum crop water productivity and 3) to evaluate sensor based border irrigation system against conventional system.

MATERIALS AND METHODS

Description of research site: This experimental research work was carried out at Postgraduate Agriculture Research Station (PARS), University of Agriculture, Faisalabad-Pakistan. It is part of land situated in Rachna Doab (between Ravi and Chenab rivers), latitude 31.25ºN, longitude 73.09ºE and altitude 184.4m, as shown in Figure 1. The geographical structure of Rachna Doab is comparatively smooth with a slope of land surface fluctuating from 0.25 m km^{-1} in north south and northeast less than 0.2 m km^{-1} to south and southwest (Ahmad *et al.*, 2009).

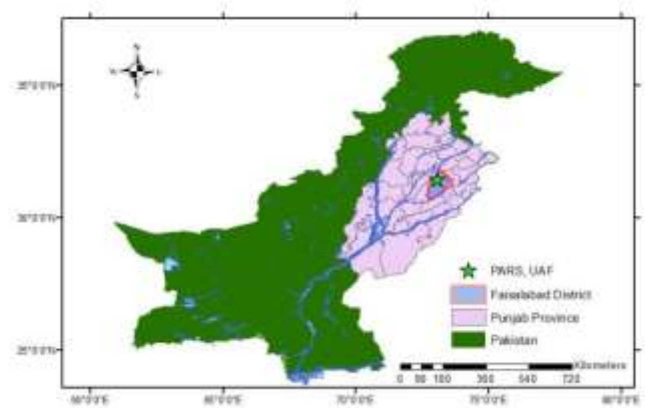

Figure 1. Location of experimental site.

The size of filed was 33.84m × 27.44m for experiment and it was divided into 30 equal grids. The size of each grid was 5.64m × 5.488m and soil samples were collected at the depth of 9 inches (23cm) from each grid for its physical and chemical analysis. Field capacity at experimental field area was measured by soil moisture tester. The soil was classified to sandy loam according to the United State Department of Agriculture (USDA) on the basis of textural classification.

Metrological data such as temperature, humidity, sunshine hours, wind speed and solar radiation were recorded from Crop Physiology Department, University of Agriculture, Faisalabad-Pakistan. The Faisalabad city has varied in temperature and touches two extremes, maximum temperature in summer (May, June and July) up to 48 ºC and may fall up to 0 ºC in winter (December, January and February).

Hydraulic simulation of surface irrigation system: The WinSRFR 4.1.3 was utilized in present research for simulation of surface irrigation system that was developed by USDA (USDA-ALARC, 2009). WinSRFR is the latest and most widely used model for this purpose (Ali, 2011; Chen *et* *al.*, 2013; Campo-Bescos *et al.*, 2015; Roldán-Canas *et al.*, 2015; Akbar *et al.*, 2016). It is user friendly and contains integrated model packages of SRFR for surface irrigation such as basin, border and furrow, also including BASIN for level basin design program and BORDER for sloping border-strip (Clemmens *et al.*, 1995; Strelkoff *et al.*, 1998). The WinSRFR model has diversified hydraulic functional characterization such as event analysis, simulation, physical design and operational analysis. The first functional property estimates the efficiency of irrigational event on the basis of measured data and assesses the infiltration properties of soil to run the simulation process to get outputs like flow, hydrographs of depth and potential profile of infiltration. The physical design functional characteristic is to determine best dimensions for surface irrigation system. However, operational analysis functionality is to estimate the superlative combination of management approaches of inflow and time to cutoff.

Unlike other similar models, WinSRFR services specific procedures of the momentum calculation i.e., the zero-inertia or kinematic wave models and has own limitations to select best suitable model according to the input data but user can also change. In theory, the zero-inertia model is perfect in evaluation through a full hydrodynamic model using distinctive irrigation situations. WinSRFR chooses the zero-inertia model when the field bottommost gradient is lesser than 0.004 [L/L].

***Model Calibration*:** WinSRFR creates performance delineations using volume balance formulas with insecure simulation outcomes by preferring calibration at a point in solution region. The flow rate, cutoff time and infiltration parameters depends on the locality of that single directive point. After land preparation i.e. after making border of variable width and same length at the experimental site, 10 pegs of 30cm height were put into the soil along the border length at equal distance. The time was noted when water touched all of the pegs. Finally, comparison was made between advance times found from field data and WinSRFR model.

Design of experiments in WinSRFR: In the model, 90 treatments were made by several combinations of border width, discharge and inflow cutoff with respect to distance. While the other parameters such as filed length, filed slope, field depth etc. were kept constant during the simulation procedure. As, it is very difficult to install all those treatments on site. In this research, inflow rate (Q), boarder width (b) and sensor position (SP) for cutoff irrigation was variables while filed length and field slope was kept constant (Table 1). Out of all that treatments, 19 treatments (01 conventional and 18 simulated) were installed for real time experiments in the field included, 2 level of inflow rate (0.0025 and 0.0035 m^3/s) and 3,3 levels for both boarder width (6.4, 8.5 & 10.7m) and sensor position (55, 65 & 75%) of filed length, as shown in Table 2.

Table 1. Model input constants and variables.

Variables	Unit	Levels		
Inflow rate (Q)	m^3/s	Q_1= 0.0025 (2.5lps)		Q_2= 0.0035 (3.5lps)
Boarder width (B)	meter	B_1= 6.4 (21′)	B_2= 8.5 (28′)	B_3=10.7 (35′)
Sensor Position (SP) or Inflow cutoff distance	%	SP_1=55	SP_2=65	SP_3=75
Constants	**Unit**	**Value**		
Field length (L)	meter	27.43 (90′)		
Boarder depth (Y)	cm	15		
Slope	m/m	0.005		
Cutback option	-	No cutback		
Downstream condition	-	Close end		
Simulation/Solution model	-	Zero-inertia		

Table 2. Treatments combination.

Treatment number	Treatment abbreviation	Treatment variables		
		Inflow rate (Q) ($m^3/s \times 10^{-3}$)	Sensor position (SP) (%)	Boarder width (B) (m)
T_o	$Q_oS_oB_o$	Q_o = 3.5	S_1 = 90	B_1 = 8.5
T_1	$Q_1S_1B_1$	Q_1 = 2.5	S_1 = 55	B_1 = 6.4
T_2	$Q_1S_1B_2$	Q_1 = 2.5	S_1 = 55	B_2 = 8.5
T_3	$Q_1S_1B_3$	Q_1 = 2.5	S_1 = 55	B_3 = 10.7
T_4	$Q_1S_2B_1$	Q_1 = 2.5	S_2 = 65	B_1 = 6.4
T_5	$Q_1S_2B_2$	Q_1 = 2.5	S_2 = 65	B_2 = 8.5
T_6	$Q_1S_2B_3$	Q_1 = 2.5	S_2 = 65	B_3 = 10.7
T_7	$Q_1S_3B_1$	Q_1 = 2.5	S_3 = 75	B_1 = 6.4
T_8	$Q_1S_3B_2$	Q_1 = 2.5	S_3 = 75	B_2 = 8.5
T_9	$Q_1S_3B_3$	Q_1 = 2.5	S_3 = 75	B_3 = 10.7
T_{10}	$Q_2S_1B_1$	Q_2 = 3.5	S_1 = 55	B_1 = 6.4
T_{11}	$Q_2S_1B_2$	Q_2 = 3.5	S_1 = 55	B_2 = 8.5
T_{12}	$Q_2S_1B_3$	Q_2 = 3.5	S_1 = 55	B_3 = 10.7
T_{13}	$Q_2S_2B_1$	Q_2 = 3.5	S_2 = 65	B_1 = 6.4
T_{14}	$Q_2S_2B_2$	Q_2 = 3.5	S_2 = 65	B_2 = 8.5
T_{15}	$Q_2S_2B_3$	Q_2 = 3.5	S_2 = 65	B_3 = 10.7
T_{16}	$Q_2S_3B_1$	Q_2 = 3.5	S_3 = 75	B_1 = 6.4
T_{17}	$Q_2S_3B_2$	Q_2 = 3.5	S_3 = 75	B_2 = 8.5
T_{18}	$Q_2S_3B_3$	Q_2 = 3.5	S_3 = 75	B_3 = 10.7

Automation of irrigation system: In order to perform automation in surface irrigation system, soil moisture sensors were used and a networking protocol was developed to read the existing soil moisture level and data were recorded.

***Soil moisture sensor*:** In this research, spark fun soil moisture sensor (SEN-13322) was operated which reads resistance in soil, more water in soil gives less resistance and vice versa. External hardware like microcontroller was used to read this resistance variation. Furthermore, resistance can be calibrated with moisture content for useful agricultural application (Kumar *et al.*, 2018; Corwin and Lesch, 2003). This sensor gives voltage 0-5 volts depending upon amount of water in soil. Microcontroller has capability to disperse these 5 volts in 10-bit resolution e.g., 1024 parts. Sensor gave its final value between 0-1024s.

Arduino microcontroller was used in each node to collect information of each sensor and transmit it to the main server. Arduino UNO used atmega-328 chip to perform functions. It reads digital and analogue input and outputs and it was powered up with 5V USB cable with any battery. Boards were powered up by lithium-ion rechargeable battery of 3.7 volts. Microcontroller can run on these batteries upto four days. However, solar panels were used to automatically recharge the batteries during its proper function. 5v 500mA solar panels were used for this purpose.

***Networking protocol*:** The node Sensor Architecture of the micro controller and Message Queuing Telemetry Transport (MQTT) protocol was used for sensor, server and web communication. MQTT is light weight subscribing and publishing service. This protocol originally developed by IBM. Because of its light weight, simplicity and wide applications it is using successfully for wireless sensors network (Bandaranayake *et al.,* 2018; Kumar *et al.,* 2018; Alam *et al.,* 2018). To work with wireless sensor network, this protocol needs a broker, which collect information from the sensors and publish it online or website. Mosquito broker was used for this application in this system.

Main server consisted on the following hardware and software: Computer, GSM module, Relays, System power, Networking protocol and Communication Module. Credit card size, Linux operated Raspberry Pi3 model B was used in this system, which acted as server for the whole system. A microprocessor 1.2 GHz 64-bit quad core embedded in this mini-computer, which is powerful enough to handle communication between sensors. It has an integrated Wi-Fi chip, which serves the purpose the communication between sensors.

Global system for mobile (GSM) was used to send text messages to user by the server when any activity occurs in the system e.g. moisture threshold value reaches. GSM working is same as the ordinary cell phone, but it can be controlled by microcontrollers unlike cell phone. In this experiment, GSM used to send irrigation alert about the current situation of water. Moreover, relays were controlled directly with the GSM or by the server i.e. by dialing GSM sim card number, pump can be turned ON/OFF.

Field layout and land preparation: An area of 13354.6 m^2 (3.30acre) was acquired for field experiments to grow wheat crop for season 2016-17 and 2017-18. The area was further divided into two large blocks, each of equal size and named as management zone (Zone-1 and Zone-2). The field was leveled with laser land leveler and each large block was subdivided into small blocks according to the boarder width treatment size of (6.4m × 27.43m), (8.53m × 27.43m) and (10.66m × 27.43m). In each management zone, the discharge was kept constant while different level of boarder width and sensor positions were applied. The wheat (cv. Inqilab-91) sowing was completed with seed drill at seed rate of 125kg/ha with 23cm R-R distance. The recommended fertilizers containing DAP, Urea and Potash were applied at the rate of 100, 75 and 50kg/ha, respectively.

The re-installation of soil moisture sensors was executed in the center and at various lengths such as 55, 65, and 75% of each plot. The irrigated water spreads up to the designed level of lengths from sensors installed points, irrigation reach up to the tail edge of plots and stops automatically around measured the filling time. SMS facilitates in measuring soil moisture and time limitation of irrigation to prevent over and below irrigation for wheat crop production. Moreover, various plots filling time with irrigational water were also measured manually to compare it with sensor measured principles to check cutoff time of discharge. Double ring infiltrometer test, three in each management zone were conducted in the field and curve matching method was used to find average value of parameters for Kostiakov's infiltration Equation (1)

$$F = a\tau^{b} + fo \times \tau \ldots\ldots\ldots\ldots\ldots\ldots.. (1)$$

Where, τ is intake opportunity time, "a" is empirical constant, F is cumulative infiltration rate, b is empirical exponent and f_o is basic intake rate. The average result of the curve matching equation parameters were a= 50cm/hr^a, b = 0.59, fo = 0.0037, as shown in Figure 3.

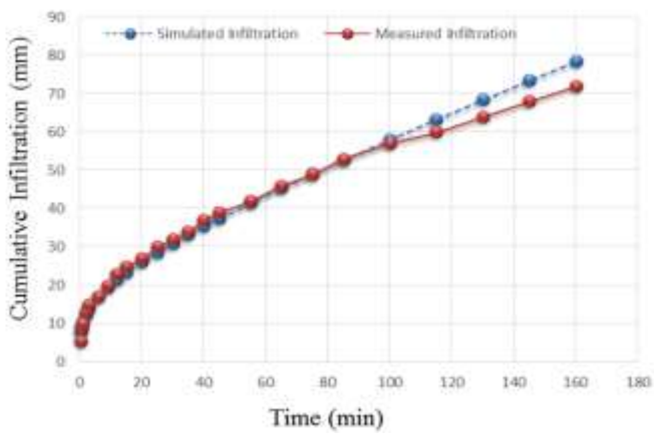

Figure 3. Measured and simulated infiltration graph.

***Depth of water required*:** The penetration of water required in each irrigation is one the most influencing factors for determine the hydraulic simulation and efficiencies. The depth of water required for each irrigation was measured by applying Equation (2) after Murty and Agarwal, (1970).

$$D_{req} = \frac{(F.C - M.C)}{100} \times SoilB.D \times RZD \ldots\ldots\ldots\ldots\ldots\ldots.. (2)$$

Where, D_{req} is depth of water required at root zone before irrigation application (m), F.C is field capacity (%), M.C is moisture content before irrigation (%), Soil B.D is soil bulk density and RZD is root zone depth (m).

***Crop Yield*:** Crop was harvested manually from three locations (one m^2 each) of each treatment at the time of harvesting. The crop yield was calculated by using Equation (3) after Murty and Agarwal, (1970).

$$Y = W_g / A \times 100 \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where, Y is crop grain yield, t / ha (tons per ha), W_g is grain weight (g) and A is area (m^2)

***Crop water productivity*:** The crop water productivity in this research was taken as the crop yield per unit area with respect to the water applied during the season, this is also referred as actual crop water productivity (Shabbir *et al.* 2012). Crop water productivity is also referred as crop production with respect to amount of water used by the crop (evapotraspiration) generally known as apparent crop water productivity but farmer normally concerned with actual crop water productivity (Jalota *et al.*, 2006). Crop water productivity of all the treatments was calculated using Equation (4) after Shabbir *et al.*, (2012).

$$CWP = \frac{\text{Grain yield (Kg/ha)}}{\text{Water applied (mm)}} \quad \text{..................(4)}$$

Statistical analysis**:** The statistical data were analyzed by following analysis of variance and means of treatments based on least significant difference test (LSD) at the 0.05 probability level through using different arrangement of statistics software but mainly minitab-2017.

RESULTS AND DISCUSSION

Soil chemical analysis: The analysis of soil samples indicates that pH varied from 7.7 to 8.7 and the available phosphorus content varies from 2 to 11 ppm. About 7% of soil samples contained high, 40% medium and 53% available phosphorus contents. Qureshi *et al.*, (2000) recommended high phosphorus content in soil, which is considered as decisive for soil fertility otherwise there is a chance of Zn deficiency in soil. The available nitrogen content in soil samples ranged from 0.017 to 0.042%. The electrical conductivity of soil describes the soluble salts present in the soil and it was varied from 0.2 to 0.6 dS/m and representing normal range as Qureshi *et al.*, (2000) described earlier that EC of the soil was normal <4 dS/m and saline for >4 dS/m.

Moisture sensors calibration**:** A successful relationship was attained between moisture content and resistivity of the sensor reading. A high coefficient of determination was found as 0.95, showing that these sensors are suitable to use for irrigation scheduling.

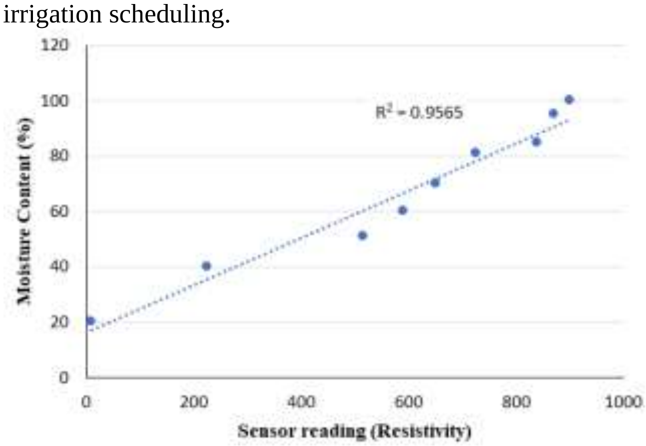

Figure 4. Calibration of soil moisture sensor

Calibration of WinSRFR model**:** Finally, comparison was achieved between advance time, calculated at experimental site and estimated by WinSRFR model during simulation. In calibration procedures some parameters such as infiltration parameters, manning's "n" etc. were slightly tuned to make model calibrated with field data. After some iterations the model was successfully calibrated with respect to advance time. The goodness of fit test indicates that values of advance time measured at field are closely matched with the values of the advance time simulated by the model, as shown in Figure 5.

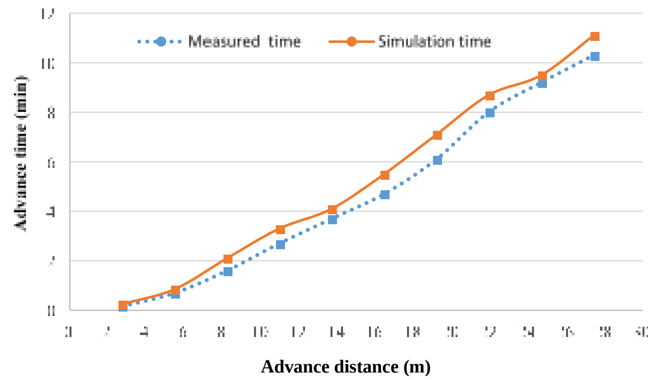

Figure 5. Calibration of WinSRFR model

WinSRFR hydraulic simulations: After successful calibration of WinSRFR model, it was subjected to determine hydraulic simulations of all treatments to avoid over or under irrigation. The performance of surface irrigation cannot accurately access by application efficiency (AE) only, there is also need some other means such as distribution uniformity minimum (DU_{min}) and distribution uniformity lower quarter (DU_{lq}) (Akbar *et al.*, 2016). Because infiltrated depth of irrigation water may reach to the targeted infiltration depth at the head of the field but may not infiltrated at the tail end (lower quarter) (Schneider and Howell, 1993; Hansen, 1960). Hence, the combination of these (AE, DU_{min} and DU_{lq}) parameters are necessary to define irrigation performance. The results of efficiency and uniformity of surface irrigation are presented in Table 3. It was found that treatment T_{10} has high efficiency and uniformity among other because all three performance indicators have higher values (AE=92, DU_{min}=87 and DU_{lq}= 91).

Plant growth parameters for wheat: The crop yield depends upon plant growth parameters such as plant population per unit area, average grains per spike, No. of tillers, plant height, spike length, number of grains per spike and 1k grain weight. The results of all these parameters are presented in Figures 6 to12. It was found that all these parameters were considerably influence by the variables of treatment.

Crop yield directly depends upon plant population per unit area. More the germination count more will be plant population that ultimately contributes towards final yield. Figure 6 clearly represents that the plant population was higher in all Q_2 treatments than Q_1. Overall, the highest plant population rate (236 number of plants m^{-2}) of wheat for both

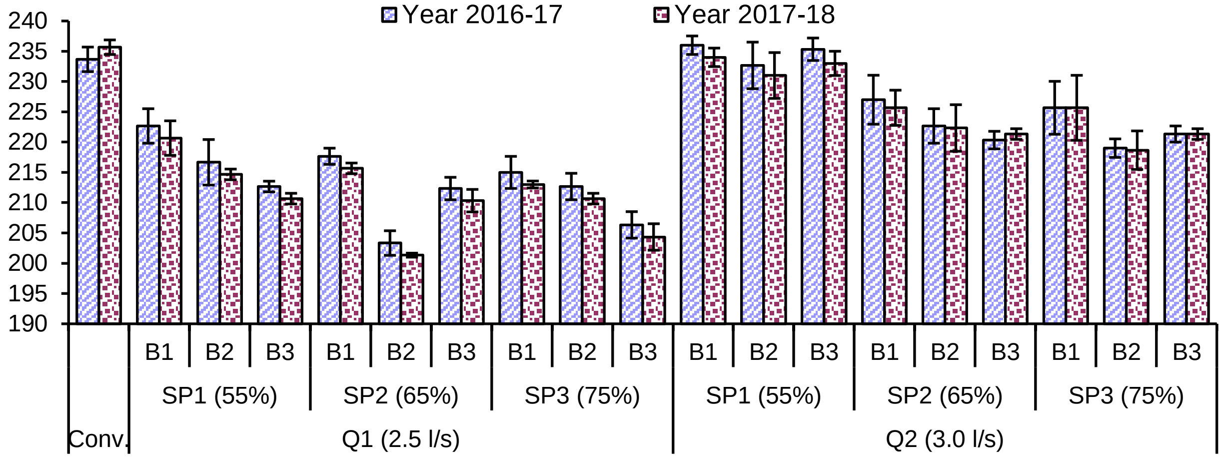

Figure 6. Average grains per spike of wheat for season 2016-17 and 2017-18

seasons were obtained in T_{10} ($Q_2S_1B_1$). The statistical analyses of No. of Tillers are given in Figure 7 and indicated highly significant difference in No. of Tillers due to different treatments in year 2016-17, whereas in year 2017-18, T_1, T_{10} and T_{11} differ significantly than others lowest value of No. of Tillers was found for T_5 conventional irrigation while T_6 and remained non-significant in year 2.

Table 3. Efficiency and uniformity simulations of calibrated WinSRFR model

Treatment Number	Treatment Abbreviation	Efficiency and Uniformity Indicators		
		AE (%)[1]	DU_{min} (%)[2]	DU_{lq} (%)[3]
T_o	$Q_oS_oB_o$	59	91	92
T_1	$Q_1S_1B_1$	93	77	73
T_2	$Q_1S_1B_2$	91	67	64
T_3	$Q_1S_1B_3$	84	45	58
T_4	$Q_1S_2B_1$	91	75	71
T_5	$Q_1S_2B_2$	85	78	60
T_6	$Q_1S_2B_3$	70	61	57
T_7	$Q_1S_3B_1$	75	73	79
T_8	$Q_1S_3B_2$	67	74	74
T_9	$Q_1S_3B_3$	60	57	61
T_{10}	$Q_2S_1B_1$	92	87	91
T_{11}	$Q_2S_1B_2$	88	78	84
T_{12}	$Q_2S_1B_3$	80	52	71
T_{13}	$Q_2S_2B_1$	81	86	90
T_{14}	$Q_2S_2B_2$	78	80	81
T_{15}	$Q_2S_2B_3$	72	60	78
T_{16}	$Q_2S_3B_1$	73	86	90
T_{17}	$Q_2S_3B_2$	61	80	81
T_{18}	$Q_2S_3B_3$	51	60	78

[1]AE= Application Efficiency (AE = Dz / D_{app}); Dz= Infiltration depth, i.e., infiltrated depth contributing to the irrigation target, D_{app}= Average depth of applied water; [2]DU_{lq} = Low-quarter distribution uniformity ($DU_{lq} = D_{lq} / D_{inf}$); D_{lq}= Lower quarter average infiltrated depth and D_{inf} =Avg. depth of infiltrated water; [3]DUmin Minimum distribution uniformity ($DU_{min} = D_{min} / D_{inf}$); D_{min} = Min. infiltrated depth; [1,2,3] (USDA-ALARC, 2009)

Simulated results predicted the significance of treatment T_{10} and T_{11} ($Q_2S_1B_2$). Average number of tillers for treatment T_{10} and T_{11} was counted as 330 and 325 respectively. Average number of tillers for T_{12} was counted 315 and 270 for year 2017 and 2018, respectively, being the lowest count in second year. These results are supported by Rao *et al.* (2016) who calculate different agronomic parameters of wheat to maximize water productivity. The data regarding plant height of wheat crop under different border width and discharge is shown in Figure 8. The minimum plant height was measured as 96.3cm in T_9 while the maximum plant height was measured as 108.44 cm in T_{14}.

Spike length is also one of the dominant yield leading factors in wheat crop. Normally, longer the spike produces higher grain yield. Dencic *et al.* (2000) reported that spikelet's per spike of wheat crop is more sensitive to irrigation for different wheat cultivars. The highest spike length of 12.8cm was found in T_1 followed by T_4 and T_5 as counted 12.5 and 12.4 cm, respectively in year 2016-17 (Figure 9). While shortest spike lengths were measured in T_{16} (9.7cm) and T_{18} (10.1cm). The maximum number of grains per spike was calculated in T_{10}, T_{11} and T_{12} that was 48, 47 and 45, respectively. While minimum number of grains per spike was calculated in T_9 and T_8 that was 30 and 31, respectively (Figure 10). The grain weight is also a major yield causative component that is affected by soil moisture and nutrient status, irrigation availability at critical stages of growth and abrupt environmental changes. Figure 11 indicated the effect of various practices of inflow rate, field width and cutoff time. The maximum grain weight was measured for the interaction of Q_2 and B_2 which was 38g. It was found that the maximum values of wheat crop growth parameters were obtained in T_{10} and T_{11} while minimum were incurred in T_8 and T_9 except for spike length.

Grain yield: Grain yield is the most essential parameter and ultimate mission of farmers. Grain yield is a result of various

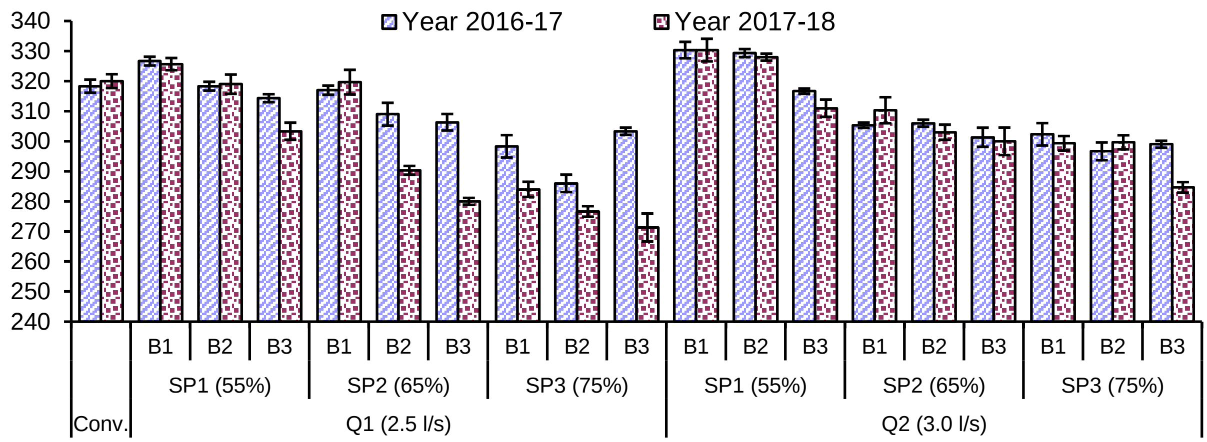

Figure 7. Number of tillers of wheat for season 2016-17 and 2017-18

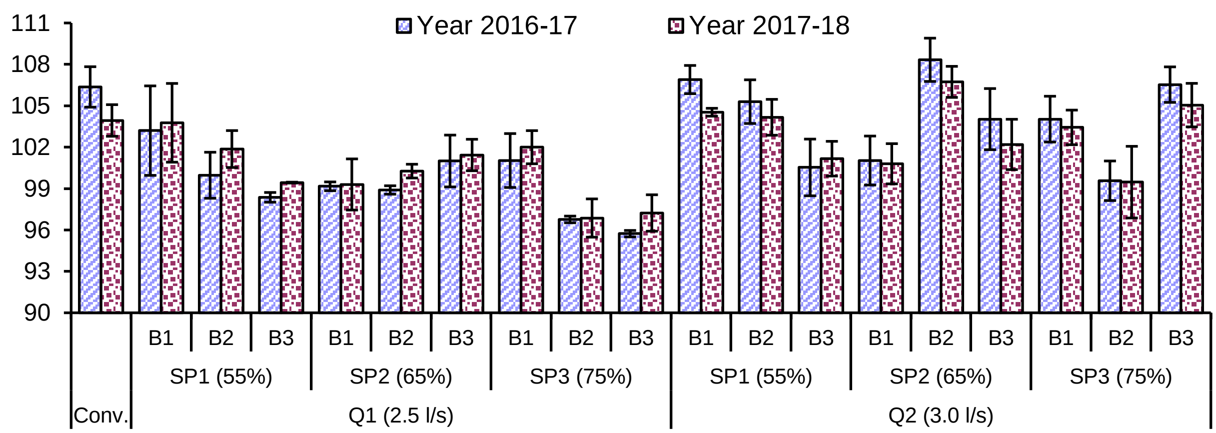

Figure 8. Plant height of wheat for season 2016-17 and 2017-18

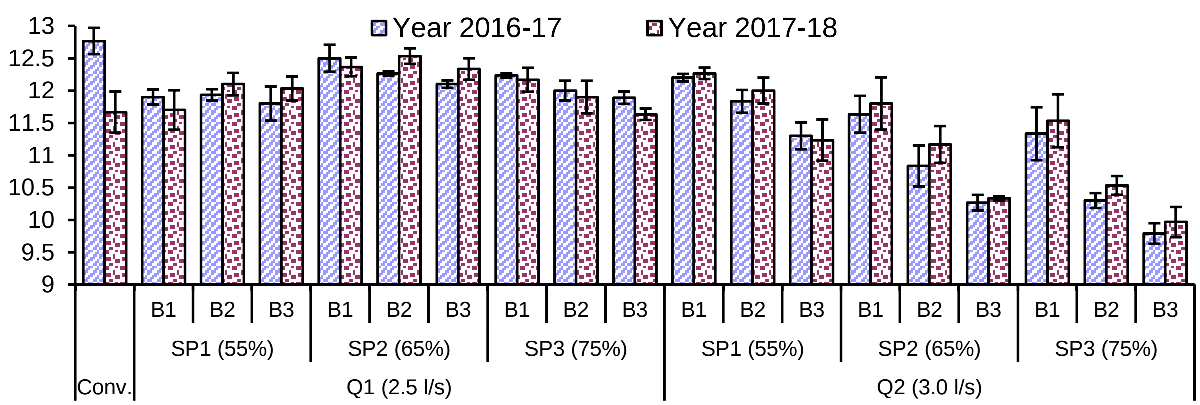

Figure 9: Spike length of wheat for season 2016-17 and 2017-18

yield contributing parameters like number of fertile tillers, No. of grains per spike and 1000-grain weight. Highest grain yield was found as 5.50 metric ton per hectare (T/ha) in T_{11}, followed by T_{12} (5.4T/ha) and T_{10} (5.35T/ha), as shown in Figure 12. The high distribution uniformity increases the water availability to the lower quarter of the field which leads towards the high crop production (Anwar and Ahmad, 2020). The reason of less wheat yields under inefficient irrigation and low distribution uniformity might be due to water stress that causes reverse osmosis (Razaq *et al.*, 2019; Ali *et al.*, 2007).

***Biological yield and harvest index*:** The biological yield is the sum of grain and straw yield. Crop vegetative growth trend is indicated by biological yield that is an index of photosynthetic efficiency. The results of biological yield show significant difference among treatments i.e., discharge and sensor position. The Effect of sensor position and border width was remained non-significant in year 1, while in year 2 all the irrigation treatments showed significant results. The highest biological yield of 13.98 T/ha was found in T_1 and lowest of 10.13T/ha in T_9.

Harvest index means the ability of crop to convert assimilate into economic parts. Higher the economic yield more will be the harvest index. Figure 14 clearly depicts that there are

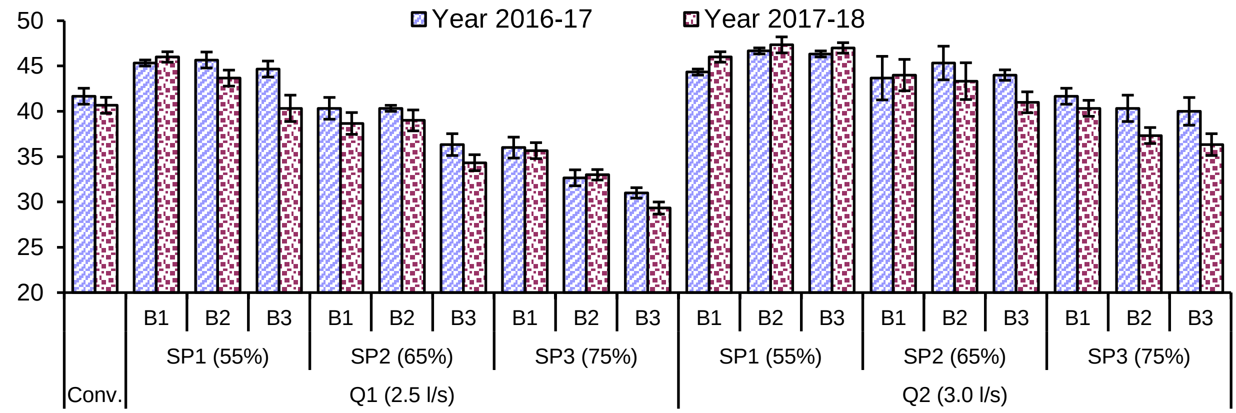

Figure 10. No. of grains per spike of wheat for season 2016-17 and 2017-18

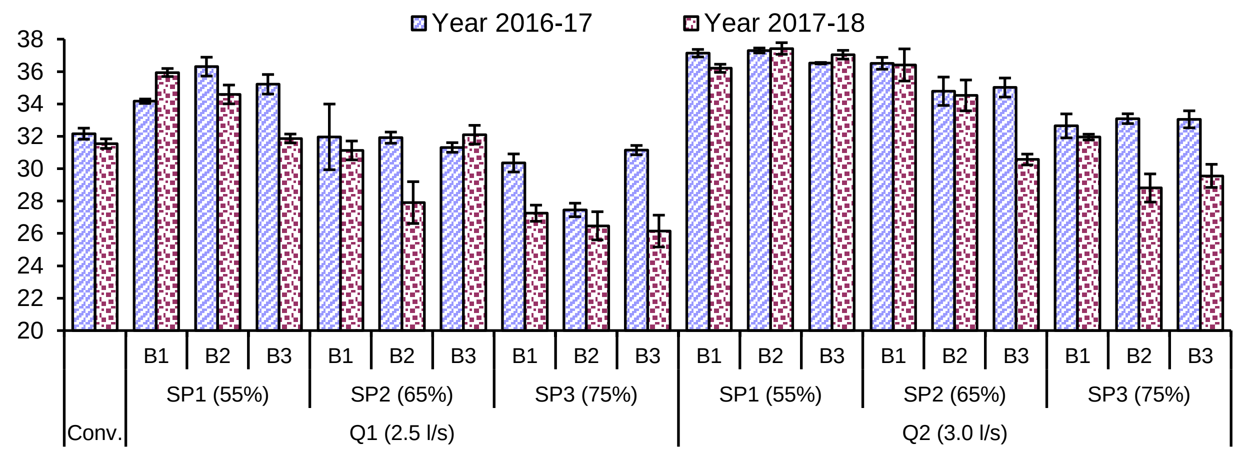

Figure 11. 1000 grains weight of wheat for season 2016-17 and 2017-18

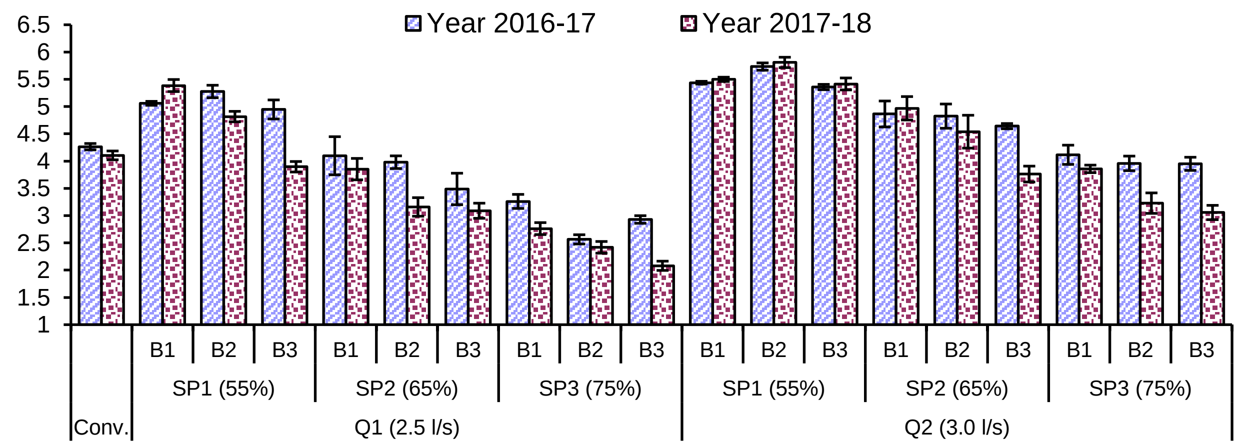

Figure 12. Grain yield of wheat for season 2016-17 and 2017-18

significant differences for harvest index (%) regarding water saving practices. The highest harvest index was found in T_{11} in year 2016-17 and in T_{12} in year 2017-18. T_8 and T_9 remained non-significant in the year 2017-18. For T_{11}, harvest index was 45%, for T_{12} it was recorded as 42% and for T_{10} average harvest index was 40%.

Depth of water applied: The depth of water applied was maintained according to sensor reading. For precise

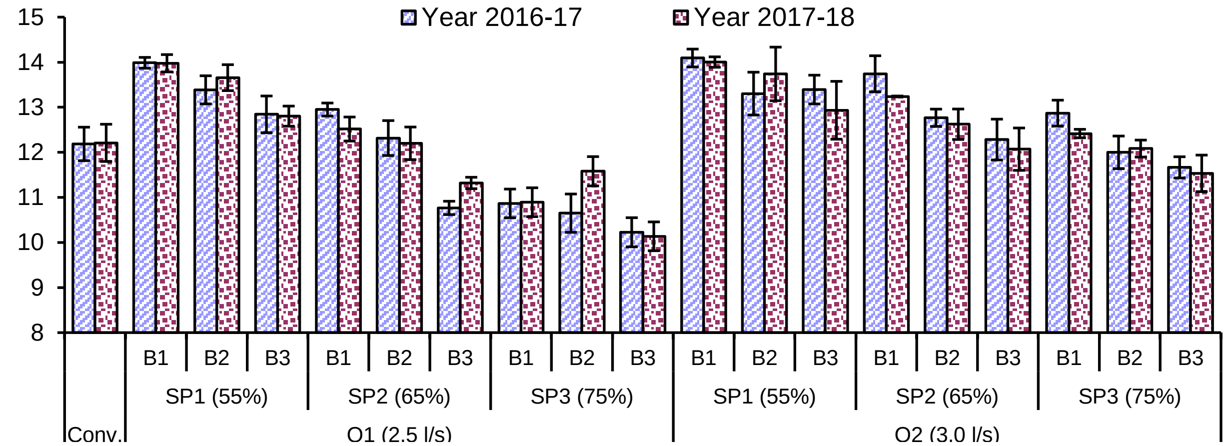

Figure13. Biological yield of wheat for season 2016-17 and 2017-18

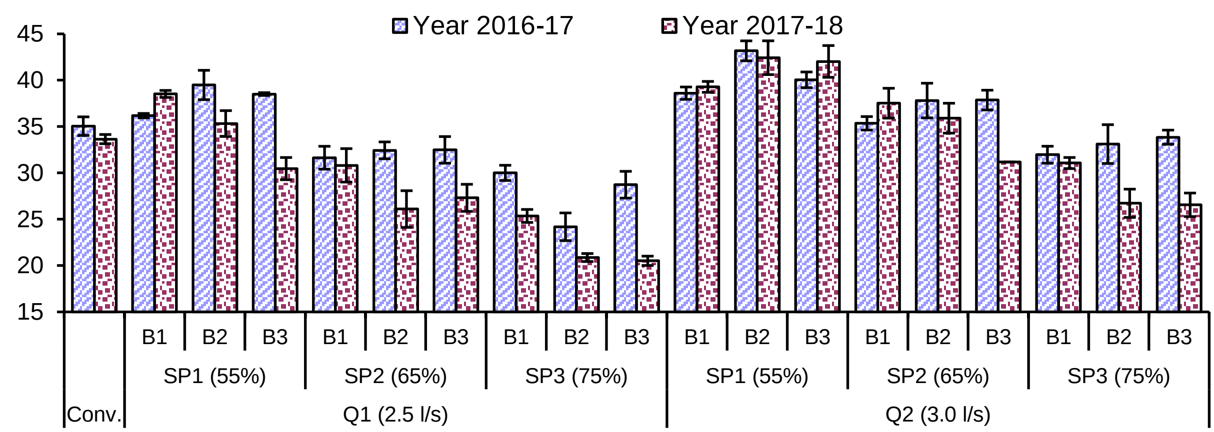

Figure 14. Harvest index per spike of wheat for season 2016-17 and 2017-18

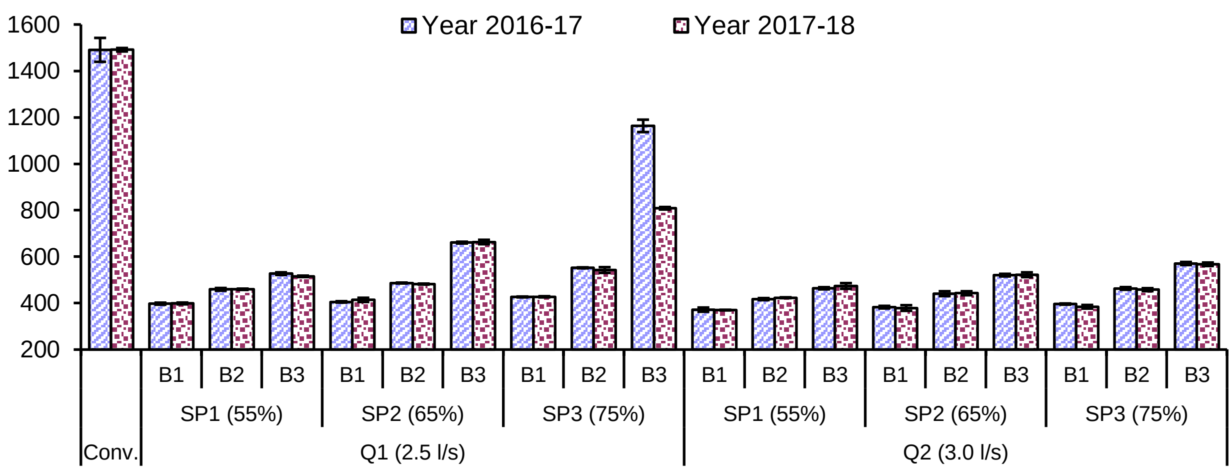

Figure 15. Depth of water applied to wheat for season 2016-17 and 2017-18

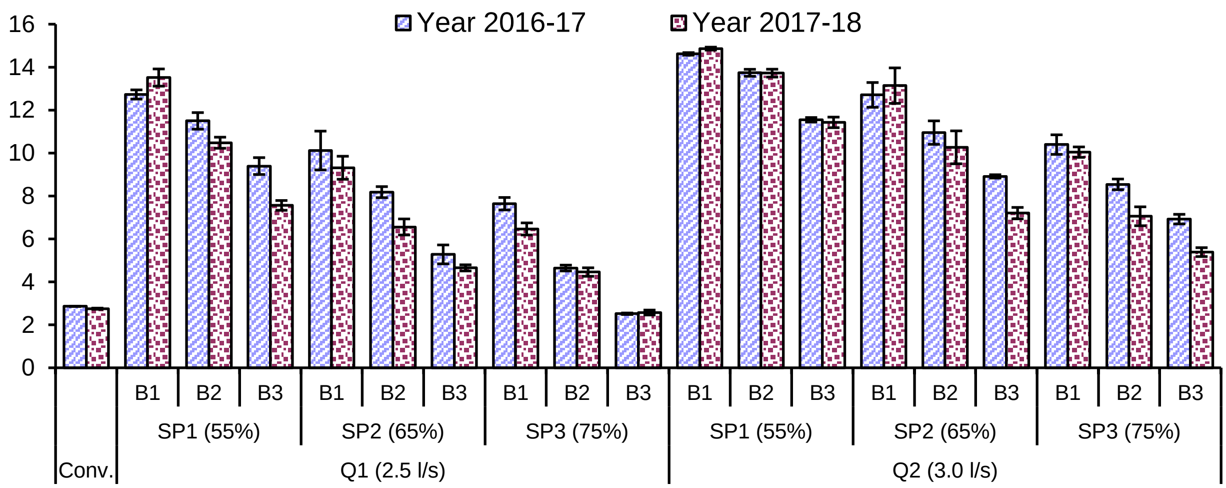

Figure 16. Water productivity of wheat for season 2016-17 and 2017-18

application of water in the field, controlled water system was used. The difference in amount of irrigation water applied in both the years was subjected to the amount of precipitation and soil moisture status by sensor, is presented in Figure 15. Two year's average minimum amount of water applied for $T_{10}$was 370mm followed by 380 mm in T_{13}, 390mm T_1 and maximum of 1491mm in control treatment (T_o). The amount of water supplied to crop decreased with the increasing discharge value. The higher discharge in surface irrigation completes its advance phase more quickly (Liu *et al.*, 2020).

***Water productivity*:** It tells how efficiently water was used by crop in the field. The difference in amount of irrigation water applied in both the years was subjected to the amount of precipitation and soil moisture status by sensor. The results of the crop water productivity of wheat for season 2016-17 and 2017-18 is presented in Figure 16. The maximum water productivity 15.76 kg/ha/mm was obtained in T_{10} followed by 13.84 kg/ha/mm in T_{11}, 13.03 kg/ha/mm in T_1 and 3.15 kg/ha/mm in control field in year 1, respectively. In Year 2, maximum water productivity 14.90 kg/ha/mm was obtained by T_{10} followed by13.62 kg/ha/mm of T_{11}, and 12.35 kg/ha/mm in treatment T_1 respectively. Lowest water productivity of 3.61 kg/ha/mm was found in conventional treatment. These results were supported by Rao *et al.*, 2016 and Wang 2017 observed similar results of wheat productivity.

Conclusions: In this experimental research study, hydraulic modeling and soil moisture sensors were used to enhance crop water productivity of wheat crop in semi-arid region of Pakistan. The irrigation applied in border field through calibrated moisture sensors were highly accurate under field conditions and saved significant amount of water with ease in operation. Among all treatments, T_{10} saved maximum water (1120mm) and achieved maximum water productivity of 11.93 kg/ha/mm as compared to the controlled treatment followed by T_{11}, T_1 and T_{13}. Efficiency and uniformity indicators have higher values in all treatments of Q_2 (T_{10} to T_{18}) compare to respective Q_1 (T_1 to T_9) treatments. By increasing border width water dose not distribute in the field hence cause the decrease in water productivity. Efficiency and uniformity indicators prove that reducing boarder width, early cutoff time and high inflow rate increased hydraulic performance of surface irrigation

Treatment T_9 proved least efficient with water productivity less than the control treatment with non-significant results as predicted by the model. This treatment has maximum cutoff position and maximum border width with least discharge, which was not sufficient to irrigate the field uniformly, results in minimum water productivity. These results show that the predicted values of WinSRFR model are highly accurate and reliable. All the treatments behave as predicted by the model so simulation results of the model are reliable to use in the field.

It is clear from the results that regional research should be conducted to optimize the field dimensions using hydraulic modeling to increase crop productivity in surface irrigation system moreover, soil moisture sensors could be utilized to automate the irrigation system. In further research, filed slope and filed roughness should also be included and cost-benefit ratio needs to be calculated with life of sensing systems.

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