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Evaluating water application efficiency of low and mid elevation spray application under changing weather conditions

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ABSTRACT

Over half of the irrigated land in the US, 11.5 million ha, is irrigated with center pivot and linear move systems. Because of this, minor changes in the operation efficiency of these systems can have large impact on overall water conservation. The objective of this study was to evaluate the water application efficiency (WAE) of low and of mid elevation spray application (LESA and MESA) using catch can test and drainage lysimeters, and develop governing equations based on the weather variables. A three-year (2015–2017) field study was conducted at the Washington State University Research and Extension Center, near Prosser. Catch cans were used to collect the fraction of total irrigation-water applied that reached the ground surface as WAE and drainage lysimeters to measure the overall water loss (OAWL) and wind drift and evaporation losses (WDEL), (WDEL = 100-WAE). Air temperature (T_a), relative humidity (RH), short-wave global irradiance (R_g), wind speed (WS), and calculated vapor pressure deficit (VPD) were used as the input weather variables to mixed modeling technique. Results showed that on average 21% more irrigation-water reached the ground with LESA than with MESA systems. Lysimetric measurements showed on average a 16% efficiency difference between MESA and LESA. The monthly WAE differences between MESA and LESA increased from 12 to 30% during the hot summer months and thereafter decreased, from 30 to 9%. The warmer and drier year of 2015 had the highest annual average values of WDEL of 17% for LESA and 19% for MESA. Results indicated a relatively constant WAE for LESA regardless of weather conditions. Mixed modelling showed that VPD was the only significant predictor ($P < 0.05$) of WAE for LESA, while VPD and WS for MESA. Our results might be used to adjust center pivot travel speed (% settings) to compensate for variations in WAE as the weather changes.

1. Introduction

Agriculture is the largest consumer of available fresh water resources 70–80% in the leading agricultural states of the US (Hoekstra and Chapagain, 2006). An increasing water scarcity is forecasted due to increasing population and consequent food demand, climate change, and with an increasing water demand to grow biofuel crops (Boserup, 2011; Gheysari et al., 2015). In arid regions, agriculture depends on irrigation, which is responsible for more than 90% of the consumptive water use (Döll et al., 2009). Also Scanlon et al. (2007) and Shiklomanov (2000) reported that ˜90% of the fresh water resources were used for agricultural food production over the last century. Reducing water use or promoting irrigation systems with higher application efficiencies could lead toward more sustainable irrigation water management (Nair et al., 2013).

About 11.5 million ha of farmland in the US is irrigated with center pivots or linear moves (NASS, 2013). Center pivot and linear move sprinkler irrigation systems have proven to be effective and relatively consistent in their water application efficiencies and their use is increasing rapidly around the world (Spears, 2003; Sadeghi and Peters, 2013; Sadeghi et al., 2015; Mohamed et al., 2018, 2019). Large irrigated areas require large amounts of water, so even minor changes in the operation efficiency of these systems can have a large impact on overall water conservation. For example, a 15% water savings (about 120 mm) on a typical center pivot (50 ha) in the arid west will conserve enough water to supply about 300 homes (at 550 l/d) with water for a

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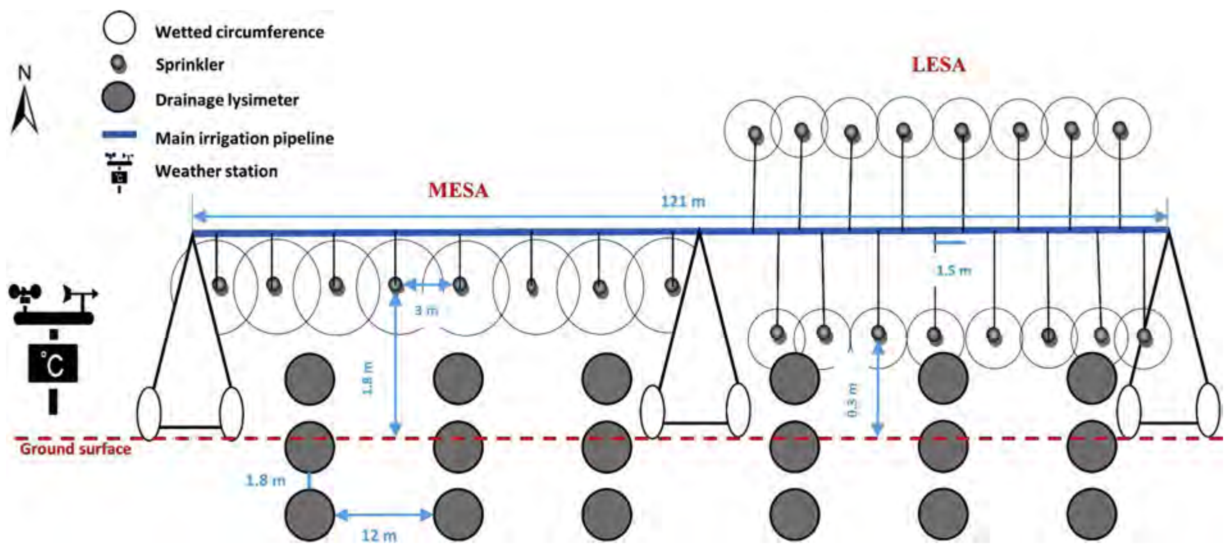

Fig. 1. Schematic diagram of the linear move (side view) with MESA and LESA sprinkler irrigation systems (Not to scale).

year.

Center pivot and linear move irrigation systems can be fitted with different type of emitters and in different ways to improve water application efficiency (WAE). These include mid elevation spray application (MESA) and low elevation spray application (LESA) (New and Fipps, 2000). The WAE range for MESA and LESA is from 70 to 80% and 80–96% respectively (Peters et al., 2016; Rajan et al., 2015).

Differences in WAE may be partially explained by the emitter's distance to the ground (Abo-Ghobar, 1992; Hermsmeier, 1973). As more water is exposed to ambient weather conditions, more is prone to wind drift and evaporation losses (WDEL) (Tarjuelo et al., 2000; Sadeghi et al., 2017). Other factors such as nozzle size, sprinkler type, and operating pressure can have minor effects on the spray losses (Yazar, 1984a; Ali and Barefoot, 1981, 1980; Tarjuelo et al., 2000). A number of studies have been conducted to evaluate how the application efficiencies and spray losses of these systems affect the design specifications for LESA, MESA, and to evaluate weather related spray losses of MESA (Abo-Ghobar, 1992; Faci et al., 2001; King et al., 2012; Ocampo et al., 2003; Ortíz et al., 2009; Playán et al., 2005; Rajan et al., 2015; Sadeghi et al., 2017; Steiner et al., 1983; Tarjuelo et al., 2000). The aforementioned research studies for sprinkler system evaluation and spray losses estimation presented regional specific empirical models to estimate these losses (including Edling, 1985; Yazar, 1984a).

The WAE studies have primarily focused on MESA and only a few studies are available for LESA (Lyle and Bordovsky, 1983; New and Fipps, 2000; Rajan et al., 2015). These studies did not involve a comprehensive evaluation of WAE and overall water losses (OAWL) for LESA and MESA. Furthermore, the above studies were aimed at the above-ground evaluation of sprinkler irrigation systems and do not provide information of water loss after its application and redistribution into the soil, like through the use of drainage lysimeters that are considered a direct method for measurement of water balance components (Feltrin et al., 2017). Our approach is different in that we took many measurements of WAE under a variety of weather conditions and using two different methods towards the development of an empirical model. Empirical equations are inherently location-based, i.e. site-specific and thus work well in the geographical area where they are developed. The empirical models suggested elsewhere in past studies might not be applicable to the climatic conditions of WA. So, this effort of developing new models, based on WA weather conditions, will be used to regulate real-time speed of moving sprinkler irrigation systems by incorporating the models into speed controlling unit of the irrigation systems to compensate for changing WAE in order to apply a uniform amount of water to the soil over time.

The objective of this study was to first evaluate WAE of LESA and MESA using catch cans and drainage lysimeters for three seasons on a continuous basis. Second, was to develop site-specific empirical models of WAE for LESA and MESA as a function of air temperature (T_a), wind speed (WS), solar radiation (R_g), vapor pressure deficit (VPD), relative humidity (RH) and grass reference evapotranspiration (ET_o).

2. Materials and methods

2.1. Linear move sprinkler system

This research was conducted at the Washington State University - Irrigated Agriculture Research and Extension Center (WSU-IAREC) near Prosser, Washington (46° 15′ 4″ N, 119° 44′ 18″ W), US in 2015, 2016 and 2017. A linear move irrigation system (Valley 8000 Series model, Valley, NE) was used for this research. The linear consisted of two spans, each 60-m long. The first span was set up as MESA and had 20 sprinklers positioned 1.8 m above the soil surface with a 3 m distance between adjacent sprinklers. All MESA sprinklers were suspended directly underneath the lateral. The second span was modified to LESA with the sprinkler drop hoses draped over the outside of the truss rods and secured with truss rod hose slings (Senninger, Clermont, FL) such that they were spread out slightly and alternately distributed (Fig. 1). The space between the LESA sprinklers was 1.5 m and the height from the soil surface was 0.3 m as given in Table 1.

The MESA sprinklers were Nelson S3000 s with yellow spinners (Nelson Irrigation Corporation, Walla Walla, WA) for 2015 and 2016 and switched to the Nelson R3030 body and the brown rotator plates in 2017. All MESA sprinklers had nozzles with a 4.37 mm diameter opening (Nelson nozzle size # 22) and used a 103 kPa pressure regulator in 2015 and 2016 and a 138 kPa pressure regulator in 2017 (Table 1). The requirements of a different experiment with this shared facility necessitated the sprinkler and pressure regulator changes in 2017.

The LESA section had Nelson D3000 sprinklers with the yellow stationary spray plate in 2015 and 2016 and then changed to the Nelson D3030 body with the brown grooved stationary spray plate in 2017. The LESA nozzles had a 3.66 mm diameter (Nelson nozzle size # 19) and used a 41 kPa pressure regulator for entire duration of the experiment (Table 1).

2.2. Weather station

A weather station was installed about 15 m southwest of the

Table 1
Key specifications of the experimental setup of the irrigation systems evaluated in our experiments.

Irrigation System	Year	Nozzle No.	Nozzle height (m)	Distance between sprinkler (m)	Pressure regulator (kPa)	Linear % setting[b]	No. of experiments	Type of data collected
LESA[a]	2015	19	0.3	1.52	41	30	10	catch cans
	2016	19	0.3	1.52	41	10, 15, 17	33	catch cans and lysimeters
	2017	19	0.3	1.52	41	7, 30	29	catch cans and lysimeters
MESA[a]	2015	22	1.8	3.04	103	30	10	catch cans
	2016	22	1.8	3.04	103	10, 15, 17	33	catch cans and lysimeters
	2017	22	1.8	3.04	138[c]	7, 30	29	catch cans and lysimeters

[a] LESA is low elevation spray application and MESA is mid elevation spray application.
[b] % linear setting is the travel speed of the linear move relative to the 100% which is 2.30 m min^{-1}.
[c] We had to change to 138 kPa instead of 103 kPa because of the shared facility. It did not affect the overall evaluation, even an increase in discharge for this year did not show an increase in losses. Losses were highest in 2015 rather than 2017.

experimental site. This weather station was managed by Washington State University (WSU) AgWeatherNet (www.weather.wsu.edu). The following weather variables were collected on a 5 s interval and averages were logged on a 15 min interval and daily basis: air temperature and relative humidity (T_a and RH) using a temperature-relative humidity probe (PC72 V; Michell Instruments Ltd., UK) at 1.5 m above ground; solar radiation (R_g) using a pyranometer (SP-110; Apogee Inc. Logan UT) at 2 m; and wind speed (WS) at 2 m using a cup anemometer (024A-L; Campbell Scientific Inc.). VPD (saturation vapor pressure, e_s, minus actual vapor pressure, e_a) and ET_o were calculated from T_a and RH, e_s was calculated using Eq. (7) and e_a by method 9 of table 3 as described in (Walter et al., 2005).

2.3. Data collection and analysis

A total of 72 experiments were conducted in the three years. Catch can data were collected in 2015–2017, while deep percolation (DP) data from drainage lysimeters were collected in 2016 and 2017. Care was taken to follow the ISO standards 7749/1 to use the catch can of diameter > 85 mm (Anonymous, 1995). The linear move was run at different speeds by assuming that the duration of irrigation did not affect the sprinkler percent losses. Catch can data was collected to measure and calculate WAE through standard catch can tests while the deep percolation data was used in the calculation of OAWL and WAE *differences* between LESA and MESA using drainage lysimeters. Data were analyzed using the mixed modeling technique (Sadeghi et al., 2017; Khosro Anjom et al., 2018).

2.3.1. Preparatory experiments

Start-up experiments were conducted before every season to get an idea of the experimental set up and to collect preliminary estimates of WAE, water application depth (WAD), deep percolation (DP), and sprinkler discharge. These warm-up trials were not included in the final analysis as it takes a few days for the lysimeters to respond (drainage water begins to flow) particularly during the hotter months (i.e., June and July).

Sprinkler discharge flow was measured manually using a volume-time technique. The average sprinkler discharge for MESA was 13.0 l min^{-1} for 2015 and 2016 and 15.5 l min^{-1} for 2017 due to the use of higher-pressure regulators. In the case of LESA, the sprinkler discharge was 6.5 l min^{-1} for 2015–2017. Experiments were conducted (water was applied with the linear move for rain gauge and lysimeter data collection) when possible on a daily basis. Some days were missed due to spray herbicide for weed control and to service the lysimeters.

2.3.2. Year 2015

In 2015, 25 cm tall graduated catch cans with a 29.3 cm diameter were used to collect the data for WAE. These cans were dug into the ground such that their openings were level with the bare soil surface. The cans were placed ˜ 2 m apart in a straight line under the lateral (Fig. 1). The collected volume in each can was measured immediately following the irrigation event. The tests were deliberately conducted under a wide variety of weather conditions during June and July. The gross water applied was calculated from: the measured linear travel speed set at 30%, the spacing between the sprinklers, and the gross flow rate from each nozzle. The nozzle flow rates were verified using a catch bucket volume and a stopwatch. This year's data were analyzed using the mixed modeling technique.

2.3.3. Year 2016

Six drainage lysimeters were installed in the fall of 2015; 3 for the LESA and 3 for the MESA irrigation system. Each lysimeter was 0.76 m deep and had an average cross-sectional area of 0.29 m^2. A collection bucket located in a separate hole with an access lid was connected to collect the drainage water. The collected deep drainage volume in each bucket was measured manually about 24 h after each irrigation. The soil was a warden silt loam (mixed, superactive, mesic Xeric Haplocambids) having an available water capacity (AWC) of 125 mm m^{-1}, a saturated hydraulic conductivity (K_{sat}) of 9 × 10^{-6} m s^{-1}, a field capacity (FC) of 16.6%, permanent wilting point (PWP) of 4.2% and bulk density (BD) of 1400 kg m^{-3} and % porosity (f) 47.2% (NRCS, 2012). No plants were allowed to grow in or around the lysimeters. Deep percolation (DP) data was acquired from the lysimeters for overall water losses (OAWL) evaluation under both systems and this data were used to estimate WAE *differences* between MESA and LESA. We also used garduted catch cans of 8.4 cm diameter in 2016. Catch can data acquisition was from 11 August until 16 September. The 15 catch cans were arranged in 3 rows around each set of 3 lysimeters. Data were analyzed using the mixed modeling technique.

2.3.4. Year 2017

Twelve additional drainage lysimeters were installed in the fall of 2016 for a total of 18 (see Fig. 1). Stratus precision rain gauges (Stratus Technologies Bermuda, Ltd.) were used to collect the amount of water delivered to the ground by each irrigation system. These rain gauges (catch cans) had a 10 cm diameter opening. They were installed in the ground such that their openings were approximately flush with the soil surface. Data were collected from 30 May to 11 September 2017 on different days but not on a continuous basis. No plants were allowed to grow in or around the drainage lysimeters. The catch can data was used to calculate WAE and WDEL measurements. Drainage lysimeter data were used for OAWL measurements to compare WAE differences between MESA and LESA through mixed modeling analysis.

2.3.5. Definitions of evaluation parameters

WAE as a % was calculated from the rain gauges measurements for both irrigation systems as Sadeghi et al., 2015:

$$\mathrm{WAE} = \frac{100 * S * L * \sum_{i=1}^{n} d_i}{n * q_{av}} \tag{1}$$

where S is average travel speed of the linear move irrigation system (that depends on the % linear speed setting) in (m s^{-1}), L is the spacing between the sprinkler heads in (m), d_i is the net depth collected by rain gauge in (m), n is number of rain gauges and q_{av} is average volume discharge of the sprinklers in (m^3 s^{-1}).

We define the WDEL as the percent loss of water from the sprinklers before it reaches the ground and is calculated as:

$$\mathrm{WDEL} = 100 - WAE \tag{2}$$

Catch can studies are unable to measure the effects that the diurnal T_a, R_g and VPD will have on the amount of water that will go into soil. So, a simple water balance approach was used with lysimeter data to estimate the over-all water losses (OAWL) under LESA and MESA sprinkler systems (Eq. (3)). The water balance approach has been widely used to estimate water balance components for hydrologic modelling under climate change, soil water monitoring, runoff estimation, and irrigation water demand (Legates and McCabe, 2005; McCabe and Wolock, 1992; Mintz and Serafini, 1992; Seginer and Kostrinsky, 1975; Shafeeque et al., 2016; Wolock and McCabe, 1999, 1999; Yates, 1996). The water balance is given by:

$$I_{gross} + P - \Delta SWC - WDEL - DP - E = 0$$
$$I_{gross} = \frac{q_{av}}{S * L} \tag{3}$$

where I_{gross} is the total amount of water discharged from the sprinkler system, P is precipitation, ΔSWC is the change in soil water content, and ET is the evapotranspiration for plants so for our scenario ET = E, i.e. evaporation of water from a bare soil surface, all units are in mm. It is assumed that when there is DP on previous days from all lysimeters (excluding the preliminary experiments), that the SWC at the time of DP was equal to FC, and that the soil water evaporation from the soil in all lysimeters (E) was equivalent and therefore the initial soil water deficit of all lysimeters was roughly equivalent. Using this assumption, we can assume that the differences in SWC (ΔSWC) in the LESA and MESA lysimeters between irrigations that resulted in DP was zero. With the lysimeter, I_{gross} and P are measured with the rain gauges and DP was measured with the drainage bucket. The efficiency difference between MESA and LESA (ΔWAE) can therefore be calculated as:

$$\Delta WAE = \left[\frac{(OAWL_{MESA} - OAWL_{LESA})}{I_{gross}} \right] \tag{4}$$

WDELs are entirely dependent on the irrigation system and the weather conditions. OAWLs are a function of WDEL, water evaporation (E) between irrigation events, and the soil's physical properties.

2.4. Predictive modeling

Mixed modeling was used to estimate the weather drivers for WAE, data analysis and final results were presented using JMP version 13.2.1 by Statistical Analysis System (SAS Institute Inc. Cary, NC, USA).

2.4.1. Mixed modeling approach

Mixed modeling is an advanced form of model fit, where fixed and random factors are jointly used. Restricted maximum likelihood (REML) was used as the method for relating the inputs to the output in the mixed modeling procedure, where non-significant independent input variables are removed from the model fit, step by step, hence left with the most significant inputs to develop the final model. The general mixed effects model is given below in Eq. (5);

$$\begin{aligned} Y &= X\beta + Z\gamma + \varepsilon \\ \gamma &\sim N(0,\ G) \\ \varepsilon &\sim N(0,\ \sigma^2 I_n) \end{aligned} \tag{5}$$

where Y is the n x 1 response vector, X is the n x p fixed effects design matrix, β with design matrix X is the p x 1 unknown fixed effects vector, Z is the n x s random effects design matrix, γ with design matrix Z is an independent s x 1 unknown random effects vector, ε is an independent n x 1 unknown random errors vector, G is the diagonal matrix of s x s having identical entries for each fixed effect, I_n is an identity matrix of order n x n and σ^2 is the residual variance. where n, p and s are number of total observations, fixed effects, and random effects, respectively. It is assumed that the error terms are normally distributed having equal treatment variances (Khosro Anjom et al., 2018).

For parameters to be included in the predictive model, a preliminary screening was performed where predictive variables with a Pearson correlation to the response variable of < 0.25 was excluded. The issue of multicollinearity was checked using a variance inflation factor (VIF) for correlation between the predictive variables (Montgomery and Runger, 2010; Al-Ghobari et al., 2018).

The assumptions of the predictive modeling method were assessed using the studentized residuals (Stnd Resids) as required for the mixed modeling procedure. Equality of variance of the Stnd Resids was evaluated to check heteroscedasticity using the median split technique where the P_{value} > 0.05 of the variance tests (Levene's test and Brown-Forsythe test) was the final decision for significance.

The test that Stnd Resids must be normally distributed around their mean (μ = 0) and have equal variance, is a key factor for the final predictive model to be fit or not. Normality of the residuals was statistically assessed using Wilk-Shapiro test. The global analysis of variance test makes sure that the overall model is fit to use or not with a P_{value} < 0.05.

3. Results and discussion

3.1. Mean statistics

The evaluation parameters for the LESA and MESA sprinkler

Table 2
Significance statistics for the evaluation parameters of LESA and MESA for the three years(2015–2017) study.

	t Ratio	$P_{value\ @\ 0.05\ level}$	MESA[b] Mean (SD)[a]	LESA[b] Mean (SD)
WAE (%)[a]	−6.085	< 0.0001	80 (12)	97 (22)
WAD (mm)[a,c]	−1.451	0.1489	17 (10)	20 (13)
WDEL (%)[a]	4.513	< 0.0001	19 (12)	4 (22)

[a] WAE is water application efficiency, WAD is water application depth, WDEL is wind drift and evaporation losses and SD is the standard deviation.
[b] LESA and MESA are low and mid elevation spray application.
[c] Test of means for d_{gross} during 2015–2017 was non-significant (P_{value} = 0.0905) between LESA and MESA.

irrigation systems (WAE, water application depth (WAD), and WDEL) were tested to see if their mean values were statistically different. For this a simple *t*-test for differences in the means was used at a 95% confidence interval. All the parameters were found to be significantly different between LESA and MESA from each other with a $P_{value} < 0.05$ except for WAD because the effect of different gross application depths has much less effect on the % WAE of both systems as shown in Table 2 (Lyle and Bordovsky, 1983; Peters et al., 2016).

The graphical spread along with the statistics of the mean values of both LESA and MESA sprinkler irrigation systems are given in Fig.2. The one directional test statistics for WAE give a $P_{value} < 0.0001$ and clearly demonstrate that MESA WAE is significantly lower than LESA (Rajan et al., 2015). In case of WDEL and OAWL, significantly greater water losses were measured in MESA as compared to LESA.

3.2. MESA and LESA evaluation

During the 2015–2017 evaluations of the MESA and LESA sprinkler irrigation systems we found that the LESA sprinkler irrigation systems to be significantly more efficient. This method saves significant amounts of water (21%) and is practically feasible in a way that applicability of the LESA system is cost effective, energy efficient along with high WAE as has been shown by others (Johnson et al., 2001; Schneider, 2000; Schneider and Howell, 1990; Tolk et al., 1995). This is particularly true when we are concerned about the overall losses (system design and field condition losses) as provided in Table 2 and Fig. 2a and b. From 2015 to 2017, an average difference between LESA and MESA of 18% was measured in WAE and WDEL. The ΔWAE using the OAWL differences measured in the lysimeters between MESA and LESA ranged from -13 to 30% with an average difference ($OAWL_{MESA} - OAWL_{LESA}$) of 14% for 2016 − 2017. Note that unlike with catch cans, with the lysimeters we could not calculate the actual WAE because E was unknown during the irrigation intervals, but only the ΔWAE (*difference* in WAE of LESA and MESA). The actual expected % savings when converting from MESA to LESA depends on the real value of WAE. For example, if the actual WAE_{MESA} is 80% and WAE_{LESA} is 94% (80% + the 14% difference) then the expected additional water to the ground per m^3 pumped would be 14/80 = 17.5%. The expected savings will be a minimum of 16% (14% / (100%-14%)).

3.2.1. Mid elevation spray application (MESA)

Our trials show that the WAE of MESA ranged from 75 to 85% on an annual basis similar to values reported by others (Lyle and Bordovsky, 1983; New and Fipps, 2000; Rajan et al., 2015). The WDEL in MESA were measured to be a minimum of 16% in 2017 and a maximum of 26% in 2016, which are in close agreement to values from other studies (Frost and Schwalen, 1960; Steiner et al., 1983; Tarjuelo et al., 2000; Yazar, 1984a). When the trends for MESA were observed on a monthly basis throughout the entire duration (2015–2017), the WAE of MESA reached a maximum WAE of 93% in May and August having the lowest value of 78%. The trend falls in July and then rose from July to September due to changing weather conditions. The WDEL of the monthly averages for three years (2015–2017) were 6–23% with a maximum value in August and minimum in May. There was an increasing trend in the average WDEL from May to August (6–23%) and then start decreasing in September (23-17%) for all three years. For MESA, WS and VPD were the best predictors of WAE as discussed before (Frost and Schwalen, 1960, 1955; Kraus, 1966).

3.2.2. Low elevation spray application (LESA)

For LESA there was a difference in all of the evaluation parameters on a monthly and annual basis. Average WAE ranged from 118% in 2017 to 78% in 2016 (Peters et al., 2016; Rajan et al., 2015). The WAE values > 100% are possible due to the non-uniformity of the fixed stream sprinklers used and therefore variations in catch can readings with some cans getting more (direct path of the fixed stream) and others less. The WAE being > 100% is also because of the stop-go movement of the pivot. If, during one trial, the pivot stopped such that it was filling the catch cans, and the next time it stopped in a location where it was missing the catch cans we would expect to see large differences in our irrigation application efficiencies with some days > 100%. Therefore, only averaged data is meaningful.

The average annual WDEL ranged from 6 to 18% with a minimum value in 2017 and maximum in 2016. This observation was in agreement to what others had reported on how sprinkler height from the ground affects spray losses (Hermsmeier, 1973). Monthly results of these LESA and MESA evaluation parameters were quite interesting in a way that favors LESA (Fig. 3a and b). LESA was a maximum of 115%

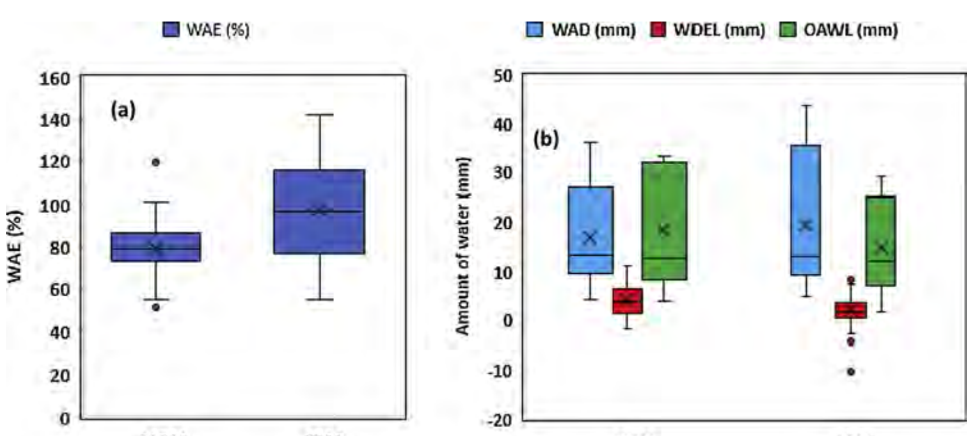

Fig. 2. Mean statistics for WAE (a), WAD, WDEL and OAWL (b) for sprinkler irrigation systems (i.e. LESA and MESA) measured during the three (2015–2017) year period. Where “x” symbol in the center of the box denote the mean and the line “– “is the median.

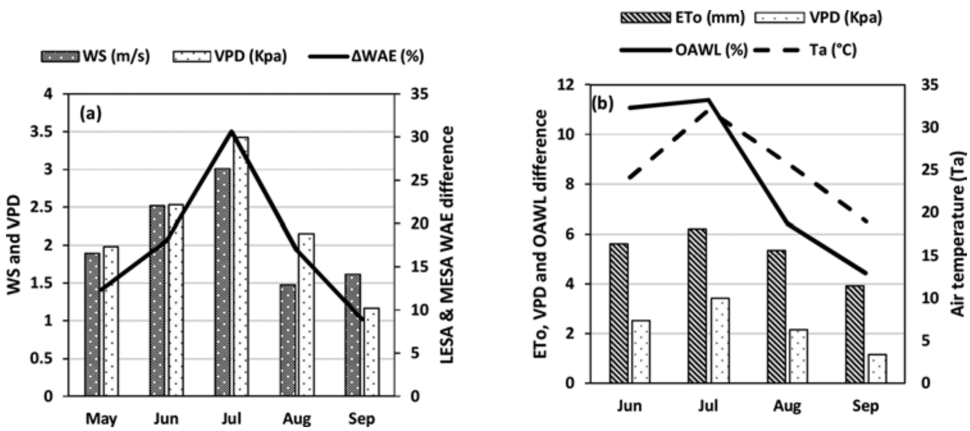

Fig. 3. WAE difference (ΔWAE) between LESA and MESA for the 2015–2017 on a monthly basis along with monthly averages for WS and VPD (a). The OAWL difference between LESA and MESA for the entire study duration (2015–2017) on monthly basis plotted together with ET_o, T_a and VPD monthly average values (b).

WAE in July and a minimum of 87% in September. The monthly averages reported here are not for the entire month as our measurements were for few days of the month.

The WDEL of LESA ranged from 0 to 14 %. A maximum of 14% losses were observed in August and 0% was the minimum in May. Abo-Ghobar (1992) showed that the height of the sprinkler from the ground was correlated with the spray losses and he observed a 20% decrease in losses as he moved the sprinkler from 2.5 m to 1.3 m. In our case we used a 1.8 m (MESA) and 0.30 m (LESA) and found a comparable average WDEL difference ($\%WDEL_{MESA} - \%WDEL_{LESA}$) of 18%. The WAE of LESA appears to depend mostly on VPD and it is less related to wind drift losses, so quite a big percentage of irrigation water losses can be mitigated by using lower sprinkler heights (i.e. LESA) (Sadeghi et al., 2017; Yazar, 1984a).

3.3. WAE predictive models

A mixed modeling technique was used to build an empirical model to estimate the effects of the temporal variability of the independent variables on the response variables (i.e. WAE). The day of the experiment (date) was considered to be a random variable. T_a, RH, WS, R_g, ET_o and VPD were explanatory/independent variables.

The overall global test for the MESA data showed the model (Eq. (6)) was significant with a Wald $P_{value} = 0.0008$. Only two independent variables WS and VPD were found to be statistically significant and these two values accounted for 95% of the variability in the response variable with R^2 Adj = 0.95 and root mean square error (RMSE) = 3% (Fig. 4a) (Yazar, 1984a). In the LESA treatment the overall global test for the predictive model (Eq. (7)) was also significant at 0.05 level. VPD ($P_{value} < 0.0001$) was the only significant variable that accounts for about 91% of the variation in the WAE of LESA with a RMSE of 9% as given in Fig. 4b (Frost and Schwalen, 1955; Clark and Finley, 1975).

$$WAE_{MESA}(\%) = 98.127 - 7.042 * WS - 2.672 * VPD \quad (6)$$

$$WAE_{LESA}(\%) = 63.36 + 15.23 * VPD \quad (7)$$

where *WS* and *VPD* are daily averages from a single irrigation event. A total of 72 experiments were used to derive these empirical models.

The MESA model residuals were plotted against calculated values of WAE for a visual check and no trends were found. The Levene's test and Brown-Forsythe test were used as the statistical check to further verify the equal variance assumption of the models. The P_{value} of Levene's test ($P_{value} = 0.0945$) and Brown-Forsythe test ($P_{value} = 0.1359$) using median split technique revealed that the Stnd Resids have equal variances. Stnd Resids of the LESA model also showed similar results and statistical tests for equal variance were not significant and the Levene's test ($P_{value} = 0.4157$) and the Brown-Forsythe test ($P_{value} = 0.5446$) validated the null hypothesis of equal variances.

The normality of the Stnd Resids were tested using the Shapiro-Wilk test, which indicated that the tests were statistically significant at 0.05 level, showing that the residuals are normally distributed with no outliers and all values are between −2.0 and 2.0.

4. Conclusions

During 2015–2017 trials of MESA and LESA sprinkler irrigation system efficiency (WAE) of center pivots and linear moves was evaluated. From these results we proposed empirical models to calculate WAE as a function of weather variables. The results indicated that on a temporal scale the WAE, WDEL and OAWL vary abruptly, but the

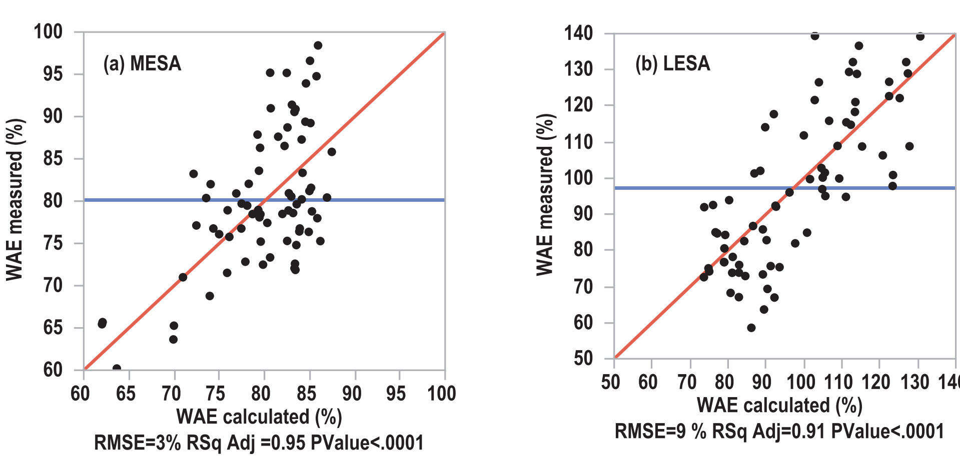

Fig. 4. Measured WAE (%) of MESA(a) versus calculated values by the fitted empirical model above (Eq. (6)), and for LESA (Eq. (7)). Statistical evaluation parameters show a good fit between the measured and calculated, goodness of fit statistics are given below the plots. The blue line is the mean value of the WAE while the red line is 1:1 line (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

differences of these parameters on a diurnal, monthly or yearly basis show that LESA is much more efficient than the MESA systems. The WAE shows an average of 21% more water reaching the ground with the given configuration of LESA than with MESA using standard catch can methods, and 16% as measured using drainage lysimeters. The WAE *difference* (WAE_{LESA} - WAE_{MESA}) was maximum in July (31%) and is much lower in the spring and in the fall. These differences can be explained by the weather in July, the warmest month of the study. The fact that the greatest savings from LESA compared with MESA happens at the time (July) of the greatest water needs, greatest water shortages, and greatest demand for power generation should be of interest to policy makers. The WDEL remained high for MESA on all of the temporal time scales and showed an overall average difference of 18% between MESA and LESA. The proposed empirical models using mixed modeling for LESA and MESA revealed that wind speed (WS) and vapor pressure deficit (VPD) are significant weather variables for predicting WAE for MESA while only VPD was significant for predicting WAE in LESA. Mixed modeling proved to be the technique that could be used in developing a relationship between predictor and response variables for MESA and LESA for WAE.

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Education

Ph.D. Biological & Agri. Engineering (CGPA=3.81) **2016 – 2019 Dec, 14**

Major: Land, Air, Water Resources, and Environmental Engineering
Supervisory committee (R. Troy Peters – Chair; Claudio O. Stockle; Jennifer C. Adam)
Washington State University, USA

M.Sc. (Hons.) Agricultural Engineering (CGPA=3.76) **2011-2013**

Major: Water Resources Management
Supervisory committee (M.J.M Cheema – Chair; Allah Bakhsh; Syed Aftab Wajid)
University of Agriculture Faisalabad, PK

B.Sc. Agricultural Engineering (CGPA=3.51) **2007-2011**
University of Agriculture Faisalabad, PK

Professional Experience

Assistant Project Scientist **Aug 2023 - to date**
Civil and Environmental Engineering, University of California Merced (UCM), California, USA

Assistant Professor **Jan 2020 – Aug 2023**
Department of Irrigation and Drainage, University of Agriculture, Faisalabad, Pakistan

Lecturer **Sep 2014 – Jan 2020**
Department of Irrigation and Drainage, University of Agriculture, Faisalabad, Pakistan

Research Assistant **Sep 2016 – Dec 2019**
Biological Systems Engineering, Washington State University, USA (Supervisor: Prof. Dr. R. Troy Peters)

Assistant Executive Engineer **Sep 2013-Sep 2014**
Department of Irrigation and Drainage, University of Agriculture, Faisalabad, Pakistan

Research Fellow **Aug 2011-Sep 2012**
The project entitled "On Farm R&D Component for the Rehabilitation of Lower Chenab Canal Part-B" was funded by Japan International Corporation Agency (JICA).
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Peer-Reviewed Publications

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1. **Sarwar, Abid**; John T Abatzoglou; Josue Medellin-Azuara; Joshua H Viers, (2025) Leveraging AI for predicting Fallow Land and Water Resource Allocation in the San Joaquin Valley of California. [In preparation for **Computer and Electronics in Agriculture**]
2. **Sarwar, Abid**; Josue Medellin-Azuara; John T Abatzoglou; Joshua H Viers, (2025) Crop water use of the Santa Clara Valley: a clustering approach. [submitted to **PLOS Water, PWAT-D-25-00013**]
3. Ikram Ullah; Aamir Raza; **Abid Sarwar**; Sheraz Maqbool; Minmin Miao, (2024). Irrigation Scheduling in crop water management: A Comprehensive review of irrigation scheduling approaches from conventional to technological advancements. **Agricultural Water Management**. **[under review, Manuscript Number: AGWAT-D-24-01223]**
4. Muhammad Waseem Rasheed; Junfang Cui; Jialiang Tang; **Abid Sarwar***; Mostafa Moradzadeh; Muhammad Faheem (2024). Assessing Spatial-Temporal Variability in Soil Moisture and the Effects of Climate Change through Hydrological Models in Hilly Landscapes. **Water Resources Management. [under review, Manuscript Number: WARM-D-24-02428]**
5. Buttar, Noman Ali; Yongguang, Hu; Ali, Basharat; Nawaz, Muhammad; Ikram, Kamran; Faisal, Muhammad; Muzammil, Muhammad; Ali, Shoaib; Khan, Muhammad; Saddique, Naeem; **Sarwar, Abid;** Raza, Ali (2024). Application of Flux variance method for estimating Surface Fluxes: Current Status and Prospective. **Applied Water Science [minor revisions submitted, EMID:52a947010013656e]**
6. Zhu, Z., Rasheed, M. W., Safdar, M., Yao, B., Tumaerbai, H., **Sarwar, A.,** & Zhu, L. (2024). Intermittent Drip Irrigation Soil Wet Front Prediction Model and Effective Water Storage Analysis. **Sustainability**, 16(21), 9553.
7. Shafeeque, M., Hafeez, M., **Sarwar, A.**, Arshad, A., Khurshid, T., Asim, M. I., ... & Dilawar, A. (2024). Quantifying future water-saving potential under climate change and groundwater recharge scenarios in Lower Chenab Canal, Indus River Basin. **Theoretical and Applied Climatology, 1-18.**
8. Ahmed E, Saddique N, Al Janabi F, Barfus K, Asghar MR, **Sarwar A**, Krebs P. Flood Predictability of One-Way and Two-Way WRF Nesting Coupled Hydrometeorological Flow Simulations in a Transboundary Chenab River Basin, Pakistan. **Remote Sensing. 2023; 15(2):457**. https://doi.org/10.3390/rs15020457
9. Aslam, R.A.; Shrestha, S.; Usman, M.N.; Khan, S.N.; Ali, S.; Sharif, M.S.; Sarwar, M.W.; Saddique, N.; **Sarwar, A**.; Ali, M.U.; Arshad, A. Integrated SWAT-MODFLOW Modeling-Based Groundwater Adaptation Policy Guidelines for Lahore, Pakistan under Projected Climate Change, and Human Development Scenarios. **Atmosphere 2022, 13, 2001.** https://doi.org/10.3390/atmos13122001
10. Khan, M.I.; Saddique, Q.; Zhu, X.; Ali, S.; Ajaz, A.; Zaman, M.; Saddique, N.; Buttar, N.A.; Arshad, R.H.; **Sarwar, A.** Establishment of Crop Water Stress Index for Sustainable Wheat Production under Climate Change in a Semi-Arid Region of Pakistan. **Atmosphere 2022, 13, 2008**. https://doi.org/10.3390/atmos13122008
11. Agregán, R.; Lorenzo, J.M.; Kumar, M.; Shariati, M.A.; Khan, M.U.; **Sarwar, A**.; Sultan, M.; Rebezov, M.; Usman, M. Anaerobic Digestion of Lignocellulose Components: Challenges and Novel Approaches. **Energies 2022, 15, 8413.** https://doi.org/10.3390/en15228413

12. Yousaf, M., Akram, M., Bhatti, I.A., Ahmad, M., Usman, M., Khan, M.U., **Sarwar, A.,** Sultan, M. and Sohoo, I., 2022. On-Site Application of Solar-Activated Membrane (Cr–Mn-Doped TiO2@ Graphene Oxide) for the Rapid Degradation of Toxic Textile Effluents. **Membranes, *12*(12), p.1178.**
13. Muhammad Shafeeque, **Abid Sarwar*,** Abdul Basit, Abdelmoneim Zakaria Mohamed, Muhammad Waseem Rasheed, Muhammad Usman Khan, Noman Ali Buttar, Naeem Saddique, Mohammad Irfan Asim, Rehan Mehmood Sabir, (2022). Quantifying impact of Billion Tree Afforestation Project (BTAP) on water yield and sediment load in Tarbela reservoir of Pakistan using SWAT model. **Land, 11(10), 1650.** https://doi.org/10.3390/land11101650
14. Noman Ali Buttar, Hu Yongguang, Josef Tanny, Ali Raza, Yasir Niaz, Muhammad Imran Khan, Naeem Saddique, **Abid Sarwar,** Ahmad Azeem, Fiaz Ahmed (2022). Estimation of sensible and latent heat fluxes using Flux Variance method under unstable conditions: A Case study of Tea Plants. **Atmosphere, 13(10), 1545.** https://doi.org/10.3390/atmos13101545
15. Rasheed, M.W.; Tang, J.; **Sarwar, A***.; Shah, S.; Saddique, N.; Khan, M.U.; Imran Khan, M.; Nawaz, S.; Shamshiri, R.R.; Aziz, M.; Sultan, M. Soil Moisture Measuring Techniques and Factors Affecting the Moisture Dynamics: A Comprehensive Review. **Sustainability 2022, *14*, 11538**. https://doi.org/10.3390/su141811538
16. Saddique, N.; Jehanzaib, M.; **Sarwar, A**.; Ahmed, E.; Muzammil, M.; Khan, M.I.; Faheem, M.; Buttar, N.A.; Ali, S.; Bernhofer, C. A Systematic Review on Farmers' Adaptation Strategies in Pakistan toward Climate Change. **Atmosphere 2022, 13, 1280.** https://doi.org/10.3390/atmos13081280
17. Saddique, N., Muzammil, M., Jahangir, I., **Sarwar, A.,** Ahmed, E., Aslam, R.A., Bernhofer, C., 2022. Hydrological evaluation of 14 satellite-based, gauge-based and reanalysis precipitation products in a data-scarce mountainous catchment. **Hydrological Sciences Journal 0, 1–15.** https://doi.org/10.1080/02626667.2021.2022152
18. Lee, J. E., Azam, M., Rehman, S. U., Waseem, M., Anjum, M. N., Afzal, A., ... **Sarwar, A.** & Rehman, S. A. U. (2022). Spatio-temporal variability of drought characteristics across Pakistan. **Paddy and Water Environment, 1-19.**
19. Shoukat, M. R., Shafeeque, M., & **Sarwar, A**. (2021). Investigating effects of deficit irrigation levels and fertilizer rates on water use efficiency and productivity based on field observations and modeling approaches**. Int J Hydro, 5(5), 252-263.**
20. **Sarwar, A.*;** R. T. Peters; M. Shafeeque; A. Z. Mohamed; A. Arshad; I. Ullah; N. Saddique; M. Muzammil; R. A. Aslam (2021). Accurate measurement of wind drift and evaporation losses could improve water application efficiency of sprinkler irrigation systems - a comparison of measuring techniques. **Agricultural Water Management, 258, 107209.**
21. Khan, M.U.; Ahmad, M.; Sultan, M.; Sohoo, I.; Ghimire, P.C.; Zahid, A.; **Sarwar, A**.; Farooq, M.; Sajjad, U.; Abdeshahian, P.; Yousaf, M. Biogas Production Potential from Livestock Manure in Pakistan. **Sustainability 2021, 13, 6751.** https://doi.org/10.3390/su13126751
22. A.Z. Mohamed, R.T. Peters, **A. Sarwar,** Behnaz Molaei, & Don McMoran (2021). Impact of the intermittency movement of center pivots on irrigation uniformity. **Water, 13 (9), 1167.**
23. Ikram Ullah, Mao Hanping, Ghulam Rasool, Gao Hongyan, Qaiser Javed, **Abid Sarwar,** Muhammad Imran Khan (2021). Effect of Deficit Irrigation and Reduced N Fertilization on Plant Growth, Root Morphology and Water Use Efficiency of Tomato Grown in Soilless Culture. **Agronomy, 11(2), 228.**
24. Muhammad Shafeeque, Arfan Arshad, Ahmed Elbaltagi, **Abid Sarwar**, Quoc Bao Pham, Shahbaz Nasir Khan, and Adil Dilawar (2021). Understanding temporary reduction in

atmospheric pollution and its impacts on coastal aquatic system during COVID-19 lockdown: A case study of South Asia. **Geomatics, Natural Hazards and Risk**, **12(1), 560-580.**

25. Behnaz Molaei, R. Troy Peters, Abdelmoneim Z Mohamed, **Abid Sarwar** (2021). Large Scale Evaluation of a LEPA/LESA system compared to MESA on Spearmint and Peppermint. **Industrial Crops and Products. 159, 113048.**
26. Rasool, A., M. Said., M. Shafeeque., I. Ahmed., H. A. EL-Serehy., S. Ali., B. Murtaza., **& A. Sarwar**. (2021) Evaluation of Arsenic contamination and potential health risk through water intake in urban and rural areas. **Human and Ecological Risk Assessment: An International Journal, 1-16.**
27. Awais, H. M., Arshad, M., Shakoor, A., Afzal, M. S., & **Sarwar, A**. (2020). Assessment of spatio-temporal fluctuations in groundwater level and its impact on tubewell energy nexus. **J. Glob. Innov. Agric. Soc. Sci, 8, 161-165.**
28. Aloqaili, F., Good, S., Finkenbiner, C., **Sarwar, A.** (2020). Using stable water isotopes to assess the influence of irrigation structural configurations on evaporation losses in semiarid agricultural systems. **Agricultural and Forest Meteorology, 108083.**
29. **Sarwar, A*.,** Peters, R. T., & Mohamed, A. Z. (2020). Linear mixed modeling and artificial neural network techniques for predicting wind drift and evaporation losses under moving sprinkler irrigation systems. **Irrigation Science, 1-12.**
30. **Sarwar, A*.,** Peters, R.T., Mehanna, H., Amini, M.Z., Mohamed, A.Z. (2019). Evaluating water application efficiency of low and mid elevation spray application under changing weather conditions. **Agricultural Water Management, 221, 84-91.**
31. A.Z. Mohamed, R.T. Peters, & **A. Sarwar.** (2019). Adjusting irrigation uniformity coefficients for unimportant variability on a small scale. **Agricultural Water Management, 213, 1078-1083.**
32. Qamar, M. U., Azmat, M., Shahid, M. A., Ganora, D., Ahmad, S., Cheema, M. J. M., Fiaz, M.A., **Sarwar, A.,** Shafeeque, M., and Khan, M. I. (2017). Rainfall extremes: a novel modeling approach for regionalization. **Water resources management, *31*(6), 1975-1994.**
33. Ajmal, U. B., Khan, M. U., Faheem, M., Tayyab, M., Majeed, M., **Sarwar, A.,** ... & Mohamed, A. M. (2017). Modification and performance evaluation of a wheat thresher. **Russian Journal of Agricultural and Socio-Economic Sciences, 65(5), 261-270.**
34. Shafeeque M., M.J.M Cheema and **A. Sarwar.** 2015. Quantification of Groundwater Abstraction using SWAT Model in Hakra Branch Canal System of Pakistan. **Pakistan Journal of Agricultural Sciences. Pak. J. Agri. Sci., Vol. 53(1): 249-255.**

Conference talks/Abstracts/Poster Presentations

*Presenting/Corresponding author

1. **Sarwar, A*.,** Medellin-Azuara, J., Abatzoglou, J. T., & Viers, J. H. (2024). Understanding water consumption in the Santa Clara Valley's main crop categories using clustering and trend analysis. AGU24, 9-13 December 2024 Washington DC.
2. **Sarwar, A***. (2024). One-day symposium on “Can agricultural landscapes be a key to sustainable water management and climate change adaptation?” Panel Discussion (Panel 1: Water Management), by CSU-WATER & 4C on September 26, 2024, Fresno State (CSU) - Peters Building, Fresno, CA.
3. Sabir, R.M., **Sarwar, A**., Wajid, S.A., Safdar, M., (2024). Estimation of evapotranspiration and yield of wheat crop using remote sensing. Abstract at the International conference on geo-

informatics for water and agricultural resources management. April 24-26, 2024, by NCGSA and Dept. of Irrigation and Drainage, UAF, (Paper ID: ICGWARM-5-CYE-6, p-68).

4. Awais, H.M., Shakoor, A., **Sarwar, A.,** Sabir, R.M., (2024). Dynamics of groundwater depletion and tubewell energy nexus in semi-arid regions – a case study of district Hafizabad, Pakistan. Abstract at the International conference on geo-informatics for water and agricultural resources management. April 24-26, 2024, by NCGSA and Dept. of Irrigation and Drainage, UAF, (Paper ID: ICGWARM-2-WAD-1, p-32).
5. Sabir, R.M., **Sarwar, A**., Safdar, M., Muzammal, H., Muhammad, N-E., Awais, H.M., (2024). Effects of Precision Irrigation on Yield of Wheat Crop in Punjab, Pakistan. Abstract at the International conference on geo-informatics for water and agricultural resources management. April 24-26, 2024, by NCGSA and Dept. of Irrigation and Drainage, UAF, (Paper ID: ICGWARM-5-CYE-7, p-69).
6. Gustavo Facincani Dourado, **Abid Sarwar**, John T Abatzoglou, Josue Medellin-Azuara, Joshua H. Viers (2023), Climate, Soils and Landscape: Applying Machine Learning and Principles of Vinecology to Sustain Current and Future Winegrowing along the Pacific Coast of the Americas, Abstract (Final poster number: GC330-1347) presented at the **American Geophysical Union (AGU) 2023**, 11-15 Dec, San Francisco, CA, USA.
7. Joshua H Viers, **Abid Sarwar***, Nicholas Santos, Kelley Moyers, John T Abatzoglou and Josue Medellin-Azuara (2023), Predicting Fallow Land and Water Management Implications Using Advances in AI for California's San Joaquin Valley, Abstract (Final paper number: GC41E-04) presented at the **American Geophysical Union (AGU) 2023**, 11-15 Dec, San Francisco, CA, USA.
8. Dourado GF, **Sarwar A,** Abatzoglou J, Medellín-Azuara J, Viers JH. (2023). Applying machine learning to sustain current and future winegrowing in California, Poster presentation at the second **AgAID Annual Review Meeting (September 14-15, 2023), Wenatchee, WA, USA**
9. Muhammad Safdar, Aamir Raza, M. Adnan Shahid, **Abid Sarwar,** Fahd Rasul, Rehan Mehmood Sabir, Hafsa Muzammal. (2023). Applications of IoT for Sustainable Agricultural Production in Pakistan. In: **International Conference on Sustainable Food Security Solutions** CPEC consortium of universities, May 29-31, 20223, Hosted by Department of Agronomy (UAF), IAEE & RD (UAF) and ISHU, University of Karachi, Pakistan
10. Aamir Raza, M. Adnan Shahid, Muhammad Safdar, **Abid Sarwar,** Rehan Mehmood Sabir, M Danish Majeed. (2023). Precision agriculture: Integrating GIS, UAVs, AI, and big data for global food security. In: **International Conference on Sustainable Food Security Solutions** CPEC consortium of universities, May 29-31, 20223, Hosted by Department of Agronomy (UAF), IAEE & RD (UAF) and ISHU, University of Karachi, Pakistan
11. M. Safdar, M. Adnan Shahid, **Abid Sarwar**, Fahd Rasul, M. Danish Majeed, Rehan M. Sabir, Hafsa Muzammal, and Usman Zafar. A critical review on wastewater applications in agriculture of Pakistan. International seminar on **Agroecological and Social Interventions of Reused Water Irrigation: A Gastroenteritis Context** held on 22-24 February 2023, organized by Department of Agronomy & Rural Sociology, University of Agriculture Faisalabad, Pakistan.
12. Usman Zafar, M. Safdar, **Abid Sarwar**, M. Adnan Shahid, Fahd Rasul, M. Danish Majeed, Rehan M. Sabir, and Hafsa Muzammal. Decolorization of textile industrial wastewater by using nano zero-valent iron: A case study of Faisalabad. International seminar on **Agroecological and Social Interventions of Reused Water Irrigation: A Gastroenteritis Context** held on 22-24 February 2023, organized by Department of Agronomy & Rural Sociology, University of Agriculture Faisalabad, Pakistan.
13. Rehan Mehmood Sabir, **Abid Sarwar**, Aamir Raza, M. Adnan Shahid, Syed Aftab Wajid, M. Safdar, Nalain E Muhammad. Yield Estimation of Wheat Crop Using Remote Sensing

Techniques. In: **International Conference on Remote Sensing, GIS, and Climate Change Applications, Strategies, Solutions & Education**.; 13–15 March 2023; Centre for Remote Sensing & Institute of Education and Research (IER) University of the Punjab, Lahore, Pakistan.

14. Muhammad Safdar, Muhammad Adnan Shahid, **Abid Sarwar**, Fahd Rasul, Muhammad Danish Majeed, Hifza Marium. Crop Modeling Using Remote Sensing Techniques. In**: International Conference on Remote Sensing, GIS, and Climate Change Applications, Strategies, Solutions & Education**.; 13–15 March 2023; Centre for Remote Sensing & Institute of Education and Research (IER) University of the Punjab, Lahore, Pakistan.
15. Safdar, M.; Shahid, M.; **Sarwar, A.;** Rasul, F.; Majeed, M.; Sabir, R. Crop Water Stress Detection Using Remote Sensing Techniques, in **Proceedings of the 7th International Electronic Conference on Water Sciences**, 15–30 March 2023, MDPI: Basel, Switzerland, doi:10.3390/ECWS-7-14198
16. Basit, A.; **Sarwar, A.;** Hussain, S.; Saleem, S.; Raza, B.; Khan, M.A.H.; Aslam, M.A. Evaluating the Impact of the Billion Tree Afforestation Project (BTAP) on Surface Water Flow in Tarbela Reservoir Using SWAT Model. **Environ. Sci. Proc. 2022, 23, 23**. https://doi.org/10.3390/environsciproc2022023023
17. **Sarwar, A.** (2022). Modeling water application efficiency and crop water status using RGB-thermal datasets. One day international seminar & training workshop on the **world water day 2022**. Organized by the Department of Irrigation and Drainage, University of Agriculture Faisalabad
18. **Sarwar, A.,** Peters, T. R., & Mohamed, A. (2019). Evaluation of twelve wind drift and evaporation loss (WDEL) empirical models through field experimentation under the climatic conditions of Prosser, Washington. In **2019 ASABE Annual International Meeting** (p. 1). American Society of Agricultural and Biological Engineers.
19. Shafeeque, M., Yi, L., Cheema, M. J. M., **Sarwar, A.,** & Asim, M. I. (2019). Assessing the Suitability of Gridded Precipitation Datasets for Hydrological Modeling Studies in Upper Indus Basin. American Water Resources Association and Center for Water Resources Research, CAS presented at the **2019 International Specialty Conference Water Security: New Technologies, Strategies, Policies, and Institutions**, 16-18 September, Beijing China
20. R. T. Peters, B. Molaei, **A. Sarwar,** & A. Z. Mohamed. (2019) Large Scale evaluation of a low energy precision application system compared to mid elevation spray application on spearmint and peppermint, In **2019 ASABE Annual International Meeting**, Boston, Massachusetts, USA.
21. **Sarwar, A.,** Peters, R.T., Mehanna, H., Amini, M.Z., Mohamed, A.Z. (2019). A Comprehensive Evaluation of Moving Sprinkler Irrigation Systems (MESA and LESA) under Dynamic Variations of Weather Conditions. **Poster presentation, GPSA Research Exposition**, March 28, CUB Ballroom Washington State University, WA.
22. **Sarwar, A.,** Peters, R.T., Mehanna, H., Amini, M.Z., Mohamed, A.Z. Molaei, B. (2018). Low elevation and Mid elevation spray application (LESA & MESA) trials under dynamic variations of weather conditions. Poster presentation**. PGSA Research Expo**, October 19. IAREC Prosser, WA.
23. R. T. Peters, H. Neibling, R. Stroh, **A. Sarwar**, B. Molaei, & A. Z. Mohamed. (2018). Low Elevation Spray Application (LESA) compared with Mid Elevation Spray Application (MESA) on Center Pivots in the Pacific Northwest. In **2018 ASABE Annual International Meeting**, Detroit USA.

24. R. T. Peters, **A. Sarwar**, M. Hani, M.Z. Amini, & A. Z. Mohamed. (2018). Center Pivot Irrigation Efficiency as a Function of Weather and Sprinkler Height. In **2018 Irrigation Association Education Conference**, Long Beach, California.
25. A.Z. Mohamed, R.T. Peters, **A. Sarwar**, & D. Mc Moran. (2018). The Accuracy of Distribution Uniformity Test under Different Moving Irrigation Systems. In **2018 ASABE Annual International Meeting**, Detroit USA.
26. **Sarwar, A.,** khot, L.R., and Peters, T.R. (2017). Applicability of low altitude multispectral sensing towards crop and site-specific adaptation of LESA. Paper presented at **Climate Impacts to water conference**, January 25-26, Skamania Lodge, Stevenson, WA. USA.
27. **Sarwar, A.,** M. Shafeeque., K. Mehmood, M. I. Asim, S. Ali and U. Maqsood. 2015. Water and energy saving through real time optimization of surface irrigation system. Abstract published in Abstract Book: **International Workshop on Renewable Energy Technologies for Community Development in Pakistan** held on November 04-06, 2015, pp. 44 (ISBN 978-969-9035-11-1).
28. Ali, S., Z. M. Khan., A. Nasir., **A. Sarwar.,** K. Mehmood., R. A. Aslam S. N. Khan., M.M. Waqas. 2015. Satellite based estimation of spatially distributed solar irradiation in Pakistan. Abstract published in Abstract Book**: International Workshop on Renewable Energy Technologies for Community Development in Pakistan** held on November 04-06, 2015, pp. 83 (ISBN 978-969-9035-11-1).
29. **Sarwar, A.,** M.S. Nasir., A. Khaliq and M. Shafeeque. 2014. Assessment of water and energy productivity of maize crop under conservative farming. Abstract published in Abstract Book: **International workshop on Renewable energy technologies in Pakistan** held on December 16-18, 2014, organized by University of Agriculture, Faisalabad and University of Kassel, Germany, pp. 60 (ISBN 978-969-9035-01-04).

Projects worked/Research collaborations

* Currently working

1. *Working as an ***Assistant Project Scientist*** in the **NSF/USDA AI Institute**: Agricultural AI for Transforming Workforce and Decision Support **(AgAID) #2021-67021-35344** and **USDA NIFA AFRI SAS Securing a Climate Resilient Water Future #2021-69012-35916** at the University of California Merced (UCM), USA ((08/2023 – to date)
2. A project of **LUMS funded by HEC** under the "Establishment of nation center in big data and cloud computing" (NCBC) **precision agriculture analytics lab (PAAL)** as a ***Co-PI*** at an estimated cost of 111.20 million PKR. (01/2020 – 06/2023)
3. An ADP project titled "Piloting precision agriculture technologies in the selected agro-ecological zones of Punjab", by **Punjab Government of Pakistan** at an estimated cost of 296 million PKR as a ***Co-PI*** *High-Efficiency Irrigation Systems* component (06/2022 – 10/2024)
4. A project titled "Assessment of freshness quality and safety of fruits and vegetables using computer vision techniques" funded by **HEC-NRPU** as a ***Team Member***, worth 11.676 million PKR. (08/2023 – 10/2024)
5. *A project titled "A strategy for sustainable sewage sludge management with energy and organic fertilizer production" funded by **HEC-NRPU** as a ***Team Member***, worth of 8.390 million PKR. (08/2023 – to date)
6. Worked as a ***Research Assistant*** on the project "Large scale evaluation and modeling of wind drift and evaporation losses under low-elevation-spray application (LESA) and mid-elevation-

spray application (MESA) in the Pacific Northwest” funded by **U.S. Department of Energy (DOE), Bonneville Power Administration (BPA), BPA-00056026** (09/2016 to 11/2019)

7. Worked as a ***Research Assistant*** on the project “Washington State University – Water Irrigation System Efficiency: Confronting insufficient water in Washington State by increasing irrigations efficiencies though education and consultation” funded by **USDA-NRCS CIG Agreement number 69-3A75-17-24** (10/2016 to 09/2019)
8. Worked as a ***Supportive Research Assistant*** on the project “Large Scale Evaluation of a low energy precision application (LEPA/LESA) system compared to MESA: Energy in Agriculture” funded by the **Washington Mint Commission, Wrigley’s, the Idaho Mint Commission, the Oregon Mint Commission, the Mint Industry Research Council (MIRC)** (01/2018 to 12/2019)

Book Chapters

*Corresponding author

1. Sabir, R.M., Kashif Mehmood, **Abid Sarwar,** Muhammad Safdar et al. (2024). Remote Sensing and Precision Agriculture: A Sustainable Future. In: Kanga, S., Singh, S.K., Shevkani, K., Pathak, V., Sajan, B. (eds) Transforming Agricultural Management for a Sustainable Future. World Sustainability Series. Springer, Cham. https://doi.org/10.1007/978-3-031-63430-7_4
2. Sabir, R.M., **Abid Sarwar,** Muhammad Shoaib, Azka Saleem et al. (2024). Managing Water Resources for Sustainable Agricultural Production. In: Kanga, S., Singh, S.K., Shevkani, K., Pathak, V., Sajan, B. (eds) Transforming Agricultural Management for a Sustainable Future. World Sustainability Series. Springer, Cham. https://doi.org/10.1007/978-3-031-63430-7_3
3. Mustafa, S., Sabir, R. M., **Sarwar, A.,** Safdar, M., Al Ansari, M. S., & Hussain, S. (2024). Precision Agriculture and Unmanned Aerial Vehicles (UAVs). In A. Khang (Ed.), Agriculture and Aquaculture Applications of Biosensors and Bioelectronics (pp. 83-108). IGI Global. https://doi.org/10.4018/979-8-3693-2069-3.ch005
4. Khan, M.U., **Sarwar, A.,** Dutta, N. and Arslan, M. (2024). The Biogas Use. In Biogas Plants: Waste Management, Energy Production and Carbon Footprint Reduction, W. Czekała (Ed.), Online ISBN:9781119863946. https://doi.org/10.1002/9781119863946.ch6
5. **Abid Sarwar,** Josué Medellín-Azuara, Joshua H. Viers (2023). Chapter 5 Economics of Microirrigation Systems: In: Microirrigation for crop production: design, operation, and management. Co-Editors; James Ayars, Daniele Zaccaria, Khaled Bali, Publishers: Elsevier, ISBN: 9780323997195. https://shop.elsevier.com/books/microirrigation-for-crop-production/ayars/978-0-323-99719-5
6. **Sarwar, A*.,** Khan, M.U. (2023). Technologies for Crop Water Stress Monitoring. In: Zhang, Q. (eds) Encyclopedia of Digital Agricultural Technologies. Springer, Cham. https://doi.org/10.1007/978-3-031-24861-0_262
7. Khan, M.U., **Sarwar, A.** (2023). Drip Fertigation Technologies. In: Zhang, Q. (eds) Encyclopedia of Digital Agricultural Technologies. Springer, Cham. https://doi.org/10.1007/978-3-031-24861-0_257
8. Fahd Rasul; Hassan Munir; Aftab Wajid; Muhammad Safdar; M. Salman Ayub; Sobia Shahzad; Rehan Mehmood; M. Adnan Shahid; **Abid Sarwar**; M. Danish Majeed; Umair Gull; Wajid Nasim Jatoi; Muhammad Mubeen; Summera Jahan and Shakeel Ahmed. (2022). Book Chapter: Sustainable Irrigation Management for Higher Yield. In Irrigation and Drainage – Recent Advances. Publishers, Intech Open. DOI: 10.5772/intechopen.107153

9. Dutta, N., Mahmood, F., **Sarwar, A**., Sultan, M., Ahmad, M., Khan, M. U., & Omar, M. M. (2022). Algae Biomass Conversion Technologies. In Handbook of Research on Algae as a Sustainable Solution for Food, Energy, and the Environment (pp. 524-546). IGI Global.
10. Khan, M. U., N. Dutta, **A. Sarwar**, M. Ahmad, M. Yousaf, Y. Kadmi, M. A. Shariati. (2021) Chapter 20, Microalgal-bacterial consortia for biomass production and wastewater treatment, Editors: Mostafa El-Sheekh and Abd El-Fatah Abomohra. In Handbook of Algal Biofuels: Aspects of Cultivation, Conversion and Biorefinery, (pp. 477-501), Publisher Elsevier, ISBN: 9780128237649
11. Cheema, M.J.M., M. Jamal and **A. Sarwar.** (2017). Channel Design and Control Structures, Chapter no. 5 in the book Applied Irrigation Engineering, Editors: A. Bakhsh and M.R. Choudhry pages 95-119, Publisher UAF, Faisalabad, (ISBN 978-969-8237-97-4). http://onlinebooks.uaf.edu.pk/Chapter.aspx?ChapId=75

Peer Reviewer Services

1. Remote Sensing (MDPI)
2. Agricultural Water Management (Elsevier)
3. Theoretical and Applied Climatology (Springer)
4. Frontiers in Earth Science (Frontiers)
5. Water (MDPI)
6. Sensors (MDPI)
7. Hydrology (MDPI)
8. Sustainability (MDPI)
9. Agriculture (MDPI)
10. Land (MDPI)

PG/UG Students supervised

** Indicates my role as a supervisory committee member. Otherwise, the research was carried out directly under my supervision as a chair of the supervisory committee*

	Name	**Research topic**	**Status**
1.	Abdul Basit (2019-ag-230), MS	Quantifying the impact of billion tree tsunami project on the sediment load in the major reservoir of Pakistan using SWAT model	Completed (PG)
2.	Muhammad Shahzad (2019-ag-338), MS	Spatial estimates of evapotranspiration using METRIC energy balance algorithm of irrigated agriculture in the province Punjab, Pakistan	Completed (PG)
3.	Muhammad Usman Abdullah (2019-ag-341), MS	Flood monitoring and damage assessment using multi-temporal satellites data: a case	Completed (PG)

		study of down-stream area of Chenab River	
4.	Rehan Mehmood Sabir (2013-ag-4456), PhD	Modeling wheat crop water productivity using high resolution remote sensing data	(Prelim. Exam defended) In progress (PG)
5.*	Hafsa Muzammal (2014-ag-4434), PhD	A multi-perspective approach to project climate change impacts on glacio-hydrology of Indus River basin	(Prelim. Exam defended) In progress (PG)
6.	Usman Zafar (2013-ag-4546), PhD	Optimization of Tarbela reservoir operation and downstream implications using HEC-Wat framework under changing climate	In progress (PG)
7.	Muhammad Rizwan Javaid (2020-ag-344), PhD	Hydraulic modeling of Taunsa-Panjnad link canal for sediment transport using HEC-RAS model	Completed (PG)
8.	Amir Nazir (2016-ag-7023), MS	Artificial intelligence based estimation of surface soil moisture a case study of Pakistan	Completed (PG)
9.*	Syeda Ammara (2021-ag-2260)	Crop yield estimation through deep learning models	Completed (PG)
10.*	Humaria Urooj (2017-ag-8632)		Completed (PG)
11.*	Nida Fatima (2021-ag-2280)	Wheat identification at different growth stages using satellite imagery	Completed (PG)
12.*	Rimsha Saddique (2017-ag-8642)		Completed (PG)
13.*	Tayyaba Abbas (2021-ag-2250)		Completed (PG)
14.	1. M. Abdur Rehman(2018-ag-7852) 2. Waseem Iqbal (2018-ag-7857) 3. Umar Farooq (2018-ag-7905)	Non – Contact Water Flow Meter	Completed (UG)
15.	1. Muhammad Asim Imran (2019-ag-8971)	Wheat Production in Faisalabad:	Completed (UG)

	2. Muhammad Tanveer (2019-ag-9022) 3. Zeeshan Ali (2019-ag-9037) 4. Noor Fatima (2019-ag-9014)	A Study of the factors that contributed to the high Yield in May 2023	
16.	Fahad Saeed (2017-ag-7533)	Development of an automatic water level monitoring system	Completed (UG)
17.	Muhammad Shahid (2017-ag-7527)	Automated fertigation applicator for existing sprinkler irrigation	Completed (UG)

Courses Taught

Courses No.	Courses title	PG/UG
ID-102/ID-304	Irrigation and Drainage Practices	UG
ID-301	Fluid Mechanics	UG
ID-604	GIS and Remote Sensing	UG
ID-502	Soil Mechanics	UG
ID-302/ID-414	Engineering Numerical Analysis	UG
ID-413	Engineering Hydrology and Climate Change	UG
ID-504	Soil and Water Conservation Engineering	UG
AENG-601/602	Project and Report I/II	UG
ID-605	Water Quality Management	UG
ID-719/ID-720	Special Problem/ Seminar	PG
ID-703	Advanced hydrology	PG

External Recognitions/Awards

- **Irrigation E3 program winner** for Irrigation Association 2019 Irrigation Show and Education Conference, Las Vegas convention center, 2-6 December, Las Vegas, NV, USA
- **Travel Award by the Biological Systems Engineering Dept. of WSU** for 2019 American Society of Agricultural and Biological Engineers (ASABE) Annual Meeting in Boston, MA, July 7-10, 2019
- **Outstanding Graduate Student Awards,** Biological Systems Engineering – 2018 WSU
- Sponsored candidate from **Water Irrigation System Evaluation (WISE)** group for **Irrigation Systems Evaluations** training course **at ITRC, California Polytechnic State University,** San Luis Obispo, CA
- Certified under FFA Course Number ALC-451 for **Part 107 Small Unmanned Aircraft**

Systems, (completion number= 0892984-20170410-00451)

- A Sponsored Participant in the **Young Water Leader Summit (YWLS) at the Singapore International Water Week (SIWW)** as a **PhD Student**, Gallery Cafe, level 2, Marina Barrage, Singapore (May 31- June 1, 2014)
- Merit based PhD Fellowship under "**50 Overseas Scholarship Program for UAF**" from university of Agriculture Faisalabad

Professional Societies Membership

- American Society of Agricultural and Biological Engineers (ASABE)
- American Geophysical Union (AGU)
- United States Committee on Irrigation and Drainage (USCID)
- Pakistan Society of Agricultural Engineers (PSAE)
- ICID Young Professional e-Forum (IYPeF)
- World Youth Parliament for Water (WYPW)
- Pakistan Engineering Council (PEC), AGRI/3500

Skills/Hydrologic models/Geospatial tools

- RS/GIS and Geospatial analysis (Python, R, and ArcGIS/QGIS)
- Energy balance models (SEBAL, METRIC, SEBS, TSEB)
- UAV data handling (Pix4D, ImageJ)
- Languages/Cloud computing (Python, R, GEE, Google Colab)
- Hydrologic/Crop modeling (SWAT, AquaCrop, SRM, HYDRUS, WEPP, HEC-HMS)
- Machine learning/Deep learning (Ensemble tree-based models, Convolutional NN, Recurrent NN, Transfer learning)
- Statistical analysis (R, JMP)

References

1.	**Name of Reference**	Dr. Troy R. Peters
	Title	Professor & Extension Irrigation Specialist
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	Relationship	Doctoral Supervisor
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	Contact Email	troy_peters@wsu.edu
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2.	**Name of Reference**	Dr. Abdelmoneim Z. Mohamed
	Title	UCCE Irrigation & Soils Advisor
	Organization	UC ANR
	Relationship	Research collaborator
	Contact Phone	(509) 781-4129
	Contact Email	amohamed@ucanr.edu

	Mailing Address	University of California Cooperative Extension 3800 Cornucopia Way, Suite A, Modesto, CA 95358, USA
3.	**Name of Reference**	Dr. Behnaz Molaei
	Title	Assistant Professor of Irrigation Engineering and Agricultural Water Management
	Organization	Tennessee State University
	Relationship	Research collaborator
	Contact Phone	(509) 781-4116
	Contact Email	bmolaei@tnstate.edu
	Mailing Address	214F Farrell-Westbrook Agricultural Complex 3500 John A Merritt Blvd, Nashville, TN 37209