Potential Impacts of Climate Change Using Long-Term Historical Climate Data on Evapotranspiration (ET) and Groundwater Contribution to Wheat and Cotton Crop

ABSTRACT

Assessing the potential impacts of climate change on crop evapotranspiration (ET), groundwater contribution (GWC) towards meeting ET and yield is crucial in allocating water resources particularly in the areas where shallow water-table depths (WTDs) are expanding on larger area. The impact of climate change on crop ET and yield has been evaluated in the past by indirect methods using simulation models. However, those models are lacking the function of GWC which is one of the most important parameters while determining ET at different water-table depths (WTDs) and its impact on yield. Direct methods (without simulation models) using long term historical weather data (observed data) provide more accurate results of climate change impact on ET, GWC towards meeting ET and yield at different WTDs. In this study, long-term historical weather data for the last 34 years (1987-2020) obtained through lysimeteric studies were analyzed to examine the trends of climatic parameters, their relationship and impact on wheat and cotton ET, GWC to ET, yield and water use efficiency (WUE). These studies were carried out during 1986-1987 and 2017-2021 periods at 1.50 m, 2.25 m, and 2.75 m WTDs in Sultanpur soil series (silt loam textured) and Miani soil series (silty clay loam textured). The mean daily temperature has increased 0.45 ^{o}C and rainfall 75.5 mm/year over a period from 1987 to 2020 which is witnessing the climate change. Wheat ET is increased, GWC contribution to ET is decreased and, yield and WUE is highest during the cropping periods of 2017-2021 as compared to 1986-1987. Climate change has decreased cotton ET and GWC towards meeting ET. It has also reduced the wheat and cotton cropping cycles by 8 days and 21 days, respectively. Higher magnitude of rainfall (during July-September) in 2019 and 2020 resulted in reducing cotton average yield of 2017-2020 compared to 1987. The study demonstrates that irrigation allocation should be increased for wheat and decreased for cotton particularly in the shallow water-table areas under Sultanpur soil type where water-table remains at 1.50 m – 2.25 m depths. Moreover, cotton crop should be cultivated by the 1st week of April, so that highest yield of cotton could be harvested before onset of monsoon.

Keywords: Rainfall, Temperature, Shallow water-table, Sultanpur soil, Miani soil, Crop yield, Water use efficiency

1. INTRODUCTION

Globally, climate change and its consequences have been witnessed. Climate change may occurs naturally, however, human activities have been proven to be the major driver to it. Since the 18th century, burning of fossil fuels such as coal, oil and gas have been increased that has resulted in producing the heat-trapping gases. The ever changing climate constitutes a major challenge and its effects being faced in developing countries (Morton, 2007). In consequences of the climate change, the mean annual global temperature has increased and precipitation patterns have been changed (Solomon et al., 2007). It has been mentioned in the 5th assessment report of the IPCC that global warming has been taken place during the recent past and will be going on during 21st century (IPCC, 2014). If climate change continued upto the end of 21st century, this may result in increasing the global mean temperature by 1.4 ^{o}C to 5.8 ^{o}C and would reduce fresh water resources substantially. This would ultimately reduce the water availability for the crops cultivation (Tadross and Wolski, 2010). Pakistan is among the most affected countries due to climate change with increasing vulnerability over time, though the country is contributing negligible to the global warming. Pakistan was ranked 12th, 8th, and 7th in 2012, 2015, and 2016, respectively, by Climate Risk Index (Kreft et al., 2014). It is projected that by the end of this century, the annual mean temperature in Pakistan is expected to rise by 3 to 5°C for a central global emissions scenario, while higher global emissions may yield a rise of 4 to 6°C (Chaudhry, 2017).

Irrigation water demands are particularly sensitive to changes in precipitation and temperature (Frederick and Major, 1997). Any change in climatic parameters will also affect crop evapotranspiration (ET). The irrigation water allocation in Pakistan is based on the previous data of crop ET. Due to climate change, the data may no longer be reliable for irrigation allocation and may result in yield loss if crop water demand is not fulfilled. For the proper irrigation water management and optimum crop production, irrigation allocation needs to be modified under the present climate change scenario. Any change in crop ET will likely have a profound effect on agriculture and water resource planning and management. Wheat and cotton are the two major crops of Pakistan which contributes significantly in the economy of Pakistan. Different studies have been conducted on assessing climate change impact on wheat and cotton crops through indirect methods by using simulation models. Some extract of the available literature on climate change impact assessment on wheat and cotton ET, yield and yield attributes through simulation models is given below.

Rajabi et al., (2022) estimated wheat ET as 686.1 mm (current situation), 819.6 mm (RCP4.5) and 840.1 mm (RCP8.5) through GFDL-ESM2M and 686.1 mm (current conditions), 731.81 mm (RCP4.5) and 748.24 mm (RCP8.5) through HadGEM2-ES model. Hordofa et al., (2022) used AquaCrop model to assess the climate change impact on wheat yield and crop water productivity in Ethiopia. They analyzed weather data for the baseline period of 1981-2020 and future period of 2026-2095. They bifurcated the baseline and future periods into wet (331 mm/year), normal (206 mm/year) and dry (133 mm) rainfall years. They found decrease in crop water productivity in the future and significant reduction in yield of wheat (60-80%) during the dry years as compared to the wet years (30-51%) and normal years (18-30%). Kiani and Iqbal (2018) while processing 25 years (1991-2015) weather data in Auto Regressive Distributed Lag (ARDL) Model found increase in wheat yield with an increase in the humidity and temperature while rainfall led to decrease the yield.

Arshad et al., (2021) used long-term historical weather data (1961-2015) to assess climate change impact on cotton growth and yield in Punjab, Pakistan. Using APSIM model, they found shrinkage of 2.30 days/decade to 5.66 days/decade in the duration between the sowing to physiological maturity, and 4.23 days/decade shrinkage in phenology stage (duration between sowing to maturity). Due to the change in climatic pattern, cotton yield was reduced by 18.2% in the growing period of 1961 to 2015. Rashid et al., (2020) processed long-term historical weather data (1981-2015) through ARDL testing model to assess climate change impact on cotton yield. The model predicted increase in yield with an increase in the rainfall and maximum temperature, while decrease in yield with the decrease in minimum temperature. Raza and Ahmad (2015) found quite different results. They analyzed 30 years data of temperature and rainfall (1981-2010) using Fixed Effect Model (validation was carried out through Hausman Test) to assess climate change impact on cotton yield in the Sindh and Punjab provinces. They found that rise of temperature was the main factor reducing cotton yield in both of the provinces. However, Sindh was found more susceptible.

These studies nevertheless, did not consider the water-table contribution to the ET while developing irrigation scheduling for wheat and cotton crops as it is a source of sub-surface irrigation reducing the irrigation water requirements (Ashraf et al., 2018). Utilization of shallow WTDs ($\leq$ 2.00 m) as subsurface irrigation leads to save substantial amount of water. This will narrow the gap between the increasing water demands due to climate change (Nosetto et al., 2009). Quantification of climate change impacts on wheat and cotton crop ET, yield and other related parameters becomes important for arid regions particularly where shallow WTDs are prevailing. About 4.48 million hectares (Mha) irrigated area of the Sindh province of Pakistan has WTD within 1.50 m and 1.06 Mha irrigated area has WTD within 1.50-3.00 m (GoP, 2015). To sustain the production of wheat and cotton crops in the arid regions like Sindh province under shallow WTDs, it is imperative to understand the impacts of changes in temperature and precipitation, and other weather parameters on crop ET, GWC towards meeting ET, yield and WUE.

No direct studies have been conducted for wheat and cotton particularly using lysimeters. Lysimeters are expensive in construction and provides facility to measure GWC that cannot be measured in open field condition. Moreover, lysimeteric studies are particularly helpful for shallow water-table areas where groundwater contribution is significant. The current study was aimed to assess the climate change impact (variation in long-term observed climatic data i.e. 1987-2020) on ET, GW contribution towards meeting ET, yield and WUE of wheat and cotton crops grown during the cropping periods of 1986-1987 and 2017-2021 at different WTDs and soil types using lysimeteric setup.

2. MATERIALS AND METHODS

2.1 Experimental Site and Design

The lysimetric experiments were performed during the cropping periods of 1986-1987 and 2017-2021. Wheat was cultivated from November to March and cotton from April to October. The experiments were conducted by using drainage-type lysimeters at Drainage and Reclamation Institute of Pakistan (DRIP), Tando Jam (25^{o} 25$^{/}$ 34$^{//}$, 68^{o} 29$^{/}$ 47$^{//}$) (Figure 1). The experiments were conducted based on the principles of randomized complete block design (RCBD) at three different WTDs (1.50 m, 2.25 m and 2.75 m from ground surface) and in two soil types (Sultanpur soil series - silt loam texture and Miani soil series - silty clay loam texture).

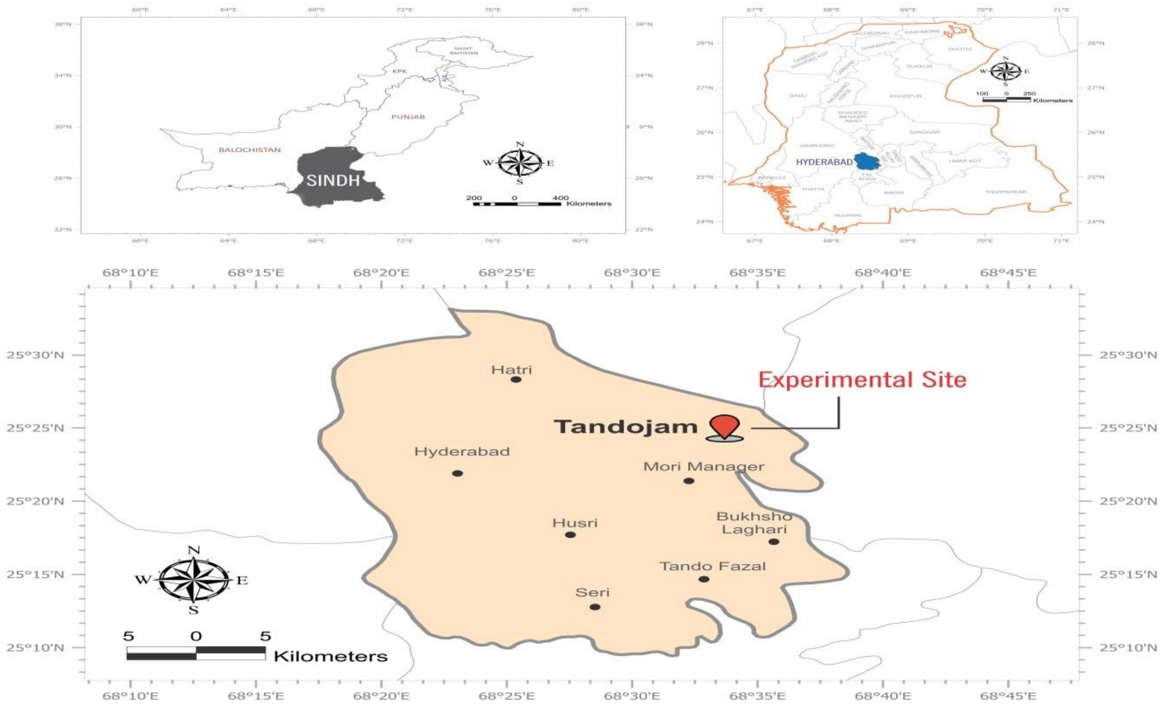

Figure 1. Location of the experimental site

2.2 Lysimeters Description

During the year 1985, with the help of Dutch Government, twelve drainage type and square shaped lysimeters were constructed at DRIP Tando Jam (Figure 2). These lysimeters are leakage proof made up of reinforced cement concrete (RCC). Each of them is measuring as 3.05 m x 3.05 m x 5.40 m and is provided with filter screens, non-calcareous spawls and graded gravel filter material, drainage outlet and water feeding arrangement. To maintain the WTDs and to measure the GW contribution to crop ET, Marriotte graduated bottles are also installed on all twelve lysimeters (Figure 3).

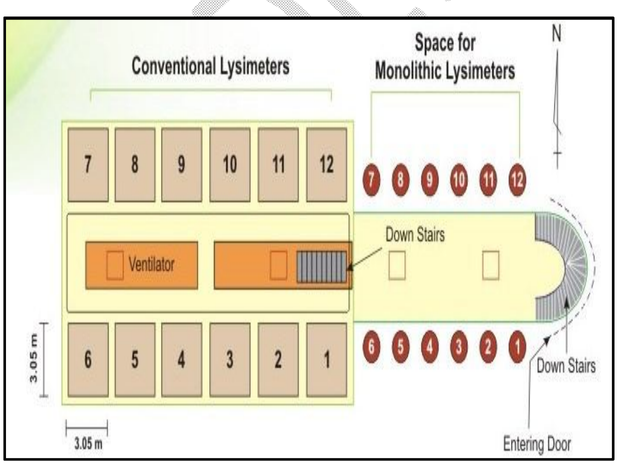

Figure 2. Schematic Diagram of Lysimeters

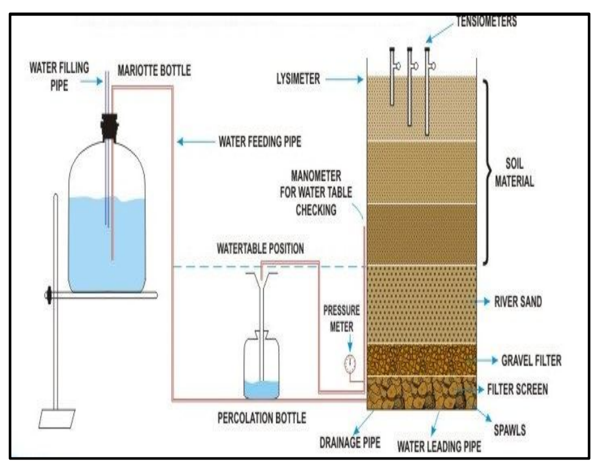

Figure 3. Diagram of equipment at lysimeters

To check the WTDs inside lysimeters, twelve piezometers each 4 m long are installed on all twelve lysimeters. Six lysimeters are filled with Sultanpur soil series and other six with Miani soil series up to a depth of 2.40 m. The remaining portion (3 m) below the soil material was filled with the filter material (river sand, gravel filter, filter screen and spawls) (Figure 4). Both soil series are representative soil types of the Sindh province.

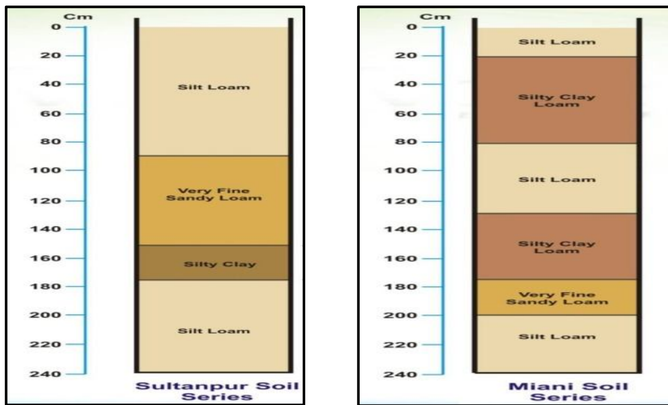

Figure 4. Diagram of the soil series filled in lysimeters

2.3 Maintenance of WTDs and GW contribution

Marriotte graduated bottles (52 liter capacities) were used to maintain the water-table (WT) at different depths (1.50, 2.25 and 2.75 m from ground surface) in the lysimeters. The mouth of each Marriotte bottle was capped with the double-hole rubber bung. From these rubber bungs, two silver tubes were passed upto the inner end of Marriotte bottle. The upper end of one silver tube (6.75 mm) was opened in the atmosphere and the second one (10 mm) was connected to the water feeding PVC rubber pipe (12.7 mm) attached at the bottom of lysimeters through gate valves. The bottom of the Marriotte bottle was positioned in line with different WT levels maintained in lysimeters. Thereafter, water from Marriotte bottle was supplied into the lysimeter to raise the WTDs. Before, commencement of the study, it took about one week to maintain the WTDs. Thereafter, soaking dose was applied and when lysimeteric soil came into the sowing condition, the crop was sown. After crop sowing, any drop in WT in a lysimeter induced the flow of water from Marriotte bottle towards the lysimeter to maintain the WTDs. The water level decline in Marriotte bottles and was compensated by re-filling the bottles completely. This enabled to measure the contribution of groundwater to meet the crop ET through subsurface irrigation.

2.4 Sowing of seeds

Wheat seed was sown at the rate of 100 kg/ha keeping 23 cm rows spacing. The cotton seeds were sown through hand driller with the seed rate of 12 kg/ha keeping the row spacing of 0.75 m. Before applying the 1st irrigation, the thinning of germinated plants was carried out to maintain the plant spacing of 20 cm (Awan *et al.*, 2011). To avoid the oasis effect (heat effect from lysimteric walls and bare land), same crops were grown around lysimeters upto a distance of 3 m.

2.5 Irrigation scheduling in lysimeters

The irrigation was applied when the available soil moisture in the crop effective root zone depleted between 50-55%. The root depth of wheat and cotton is 0.90 m. However, each crop uptakes 70% of its water and nutrients from the top 50% root zone called effective root zone depth. Hence, for irrigation scheduling purpose, gravimetric soil samples were taken layer wise upto 45 cm depth (at an interval of 15 cm). As, soil moisture depletion is equivalent to the net irrigation requirement (Allen *et al*., 1998); therefore irrigations were applied equal to moisture depleted therein the root zone (70-75 mm). The canal water was collected in a reservoir from where it was pumped to an overhead water tank (2 m high). From this tank, irrigation was applied to lysimeters through a pipeline. A water meter installed on the main inflow pipeline was used to measure the volume of water applied to each lysimeter.

2.6 Fertilizer application

The chemical fertilizers such as N, P and K were applied to wheat crop @ 120:90:60 kg/ha (Phullan *et al*., 2017). The entire quantity of P and K was applied once as basal dose during the land preparation for seed sowing. The N was split into three identical quantity and applied at the time of 1st, 2nd and 3rd irrigations. For cotton crop, NPK was applied @ 200-57-62 kg/ha (Ali *et al*., 2003). During the preparation of lysimteric soil for seed sowing, the entire dose of P and K was applied as basal dose. However, the quantity of N fertilizer was split into two identical quantities and applied during the 1st and 3rd irrigations.

2.7 Determination of crop ET

Evaporation of water from the soil surface and transpiration from plants leaves and tissues is combined in one term called evapotranspiration (ET). It is difficult to measure the both parameters separately. However, the crop ET was calculated using water balance equation given below:

$$\text{ET} = I + S + R - D \pm SMD$$

Where, ET = crop evapotranspiration (mm), I = surface irrigation (mm), S = subsurface irrigation or GW contribution (mm), R = rainfall (mm), D = drainage effluent (mm) in response to irrigation applied or rainfall occurrence, and SMS = soil moisture storage i.e. difference in soil moisture storage before sowing and after harvesting of crop.

2.8 Computation of ET_o

The reference evapotranspiration (ETo) was calculated using the Modified Penman equation (Doorenbos and Pruitt, 1975), which is given below.

$$\text{ETo} = W.Rn + (1 - W) - f(U) - (ea - ed)$$

Where, ETo = Reference evapotranspiration (mm/day), W = Temperature - related weighting factor, Rn = Net radiation in equivalent evaporation (mm/day), F (U) = Wind related function, (ea - ed) = Difference between the saturation vapor pressure at mean air temperature and mean actual vapor pressure (m bar). These parameters were further computed using the relations given by Doorenbos and Pruitt (1975). However, ETo depends on climatic data i.e. maximum and minimum temperatures, relative humidity, wind speed and sunshine hours. To record these parameters, a meteorological observatory has been installed at about 50 m from the lysimeters.

2.9 Yield and WUE

Harvesting of wheat was started when the crop ripened and turned completely to yellowish color as observed during the last three to four weeks of March. After starting flowering, cotton grows, flowers, develops bolls and produces the fibers simultaneously, even during the last fiber picking, some of the green bolls leftovers on the plants. During each cotton cropping year, 3 to 4 times cotton fiber was picked. Initially, the yield was measured for each lysimeters and converted to kilogram per hectare (kg/ha). The yield (kg) of crops under each treatment was divided by amount of water consumed (m^3) to determine water use efficiency of crops (kg/m^3).

2.10 Trend analysis of the climatic parameters

For the analysis to look at the climate change variations, the long-term temperature, rainfall, humidity, sunshine hours, wind speed, evaporation and reference evapotranspiration, data were explored for the station in study area. The long term data available was from Tando Jam station ranging from 1987 – 2020 which also defines the average climate conditions for the study area. The data were split into the two parts i.e. 1987-2003 and 2004-2020. The average of each part was made and subtracted from the other one. The difference in averages of the weather parameters is the indicator of climate change.

2.11 Statistical analysis

To compare the effects of the different WTDs and soil types, the data obtained from the lysimeters were recorded and analyzed statistically using analysis of variance (ANOVA) procedures at 95% confidence interval (α = 0.05). All statistical analysis was conducted using Statistix Software Package Version 8.1.

3. RESULTS AND DISCUSSION

3.1 Climate Change – Trend Analysis

Climate change is the long term shift in temperatures, rainfall and weather patterns. The trend of 34 years (1987 – 2020) period of climatic parameters i.e. temperature, rainfall, wind speed, sunshine hours, humidity, reference evapotranspiration and evaporation are given in Table 1. The data were divided into two parts i.e. 1987-2003 and 2004-2020. The average of each part was made and difference in averages of the climatic parameters shows the change in climate with increasing or decreasing trend over the longer period. In general the temperature, rainfall, and sunshine hours show the rising trend whereas the wind speed, humidity, reference evapotranspiration and evaporation are representing a decreasing trend.

Table 1: Climatic parameters measured at DRIP, Tando Jam

Climatic parameters	Avg. 1987-2003	Avg. 2004-2020	Increasing / decreasing trend
Temperature (^oC)	26.38	26.83	+ 0.45
Rainfall (mm)	128.6	204.1	+ 75.5
Wind speed (Knots)	3.80	2.60	- 1.20
Sunshine (Hrs/day)	8.90	9.72	+ 0.82
Humidity (%)	66.51	63.52	- 2.99
Reference ET (mm)	5.17	4.68	- 0.49
Evaporation (mm)	6.88	6.26	- 0.62

Figure 5 shows the rising trend in average annual temperature. An increase in mean daily temperature by 0.45 ^oC has been observed during 34 years period (1987-2020). The increasing temperature has shortened the cropping days, even some studies have projected shortening of crop cycle upto 50 days (Bouras *et al.*, 2019). A rising temperature may increase the crop ET due to increase in the transpiration (Peng *et al*., 2004). Moreover, crop yield may also be decreased with the rising temperature mainly because of heat stress (Herwaarden *et al*., 1998).

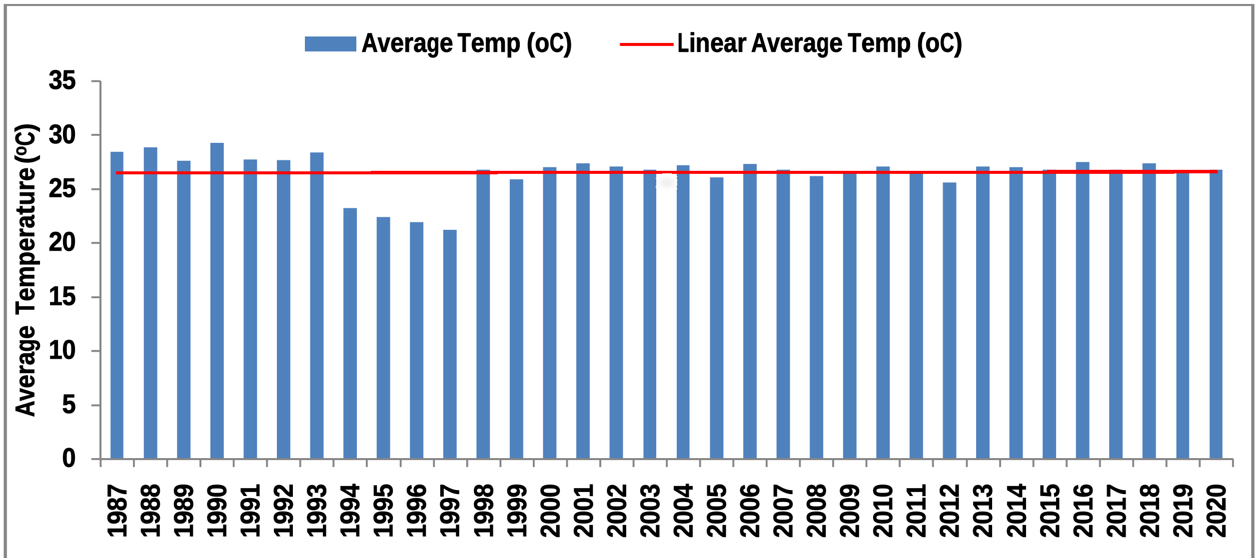

Figure 5. Temperature variation from 1987 to 2020

The magnitude of rainfall has been increased with time. Figure 6 shows the rising trend in average annual rainfall in the study area. Within a period of 34 years (1987-2020), average rainfall has increased by 75.5 mm/year. Due to inappropriate drainage system in Sindh, this will raise water-table depths leading to water-logging and salinity. High water-table (≤ 1.50 m) is already prevailing in the Sindh province (Gul et al., 2018). The situation will become worsen if the management practices shall not carry out. It is reported that an increase in magnitude, intensity and frequency of rainfall has been forecasted in the world and the net outcome impact of climate change is predicted to increase water-logging and salinity (IPCC, 2014).

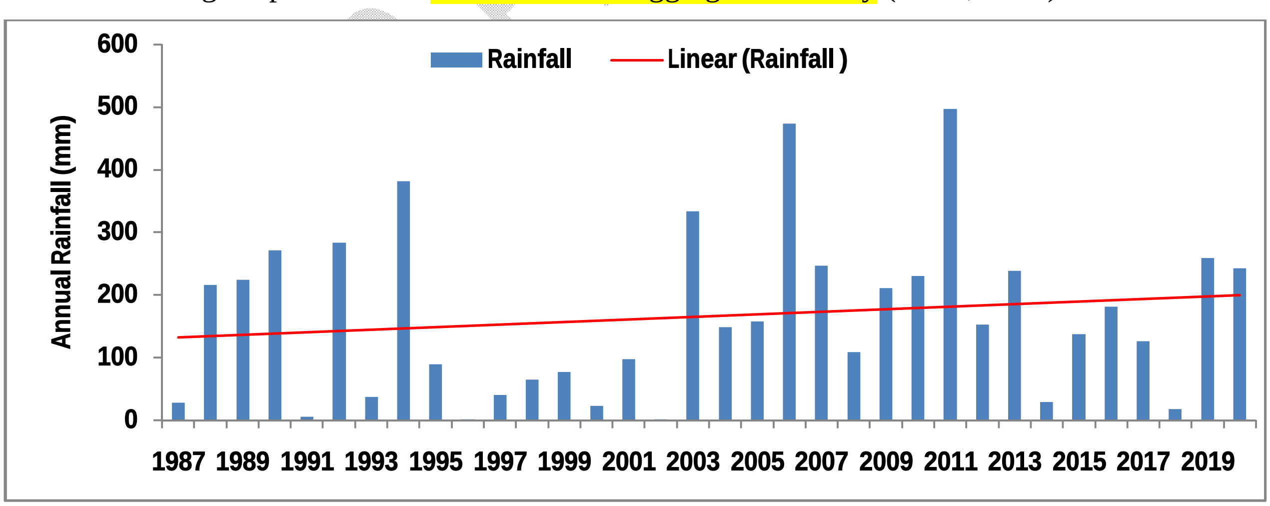

Figure 6. Rainfall variation from 1987 to 2020

Figure 7 shows the decreasing trend in average annual wind speed. A low wind speed may cause decrease in evapotranspiration since wind is governing factor in evaporation (Wang et al., 2012). Wind speed during 1987-2003 was 3.80 knots and reduced to 2.60 knots during 2004-2020. Mean daily wind speed has been decreased by 1.2 knots.

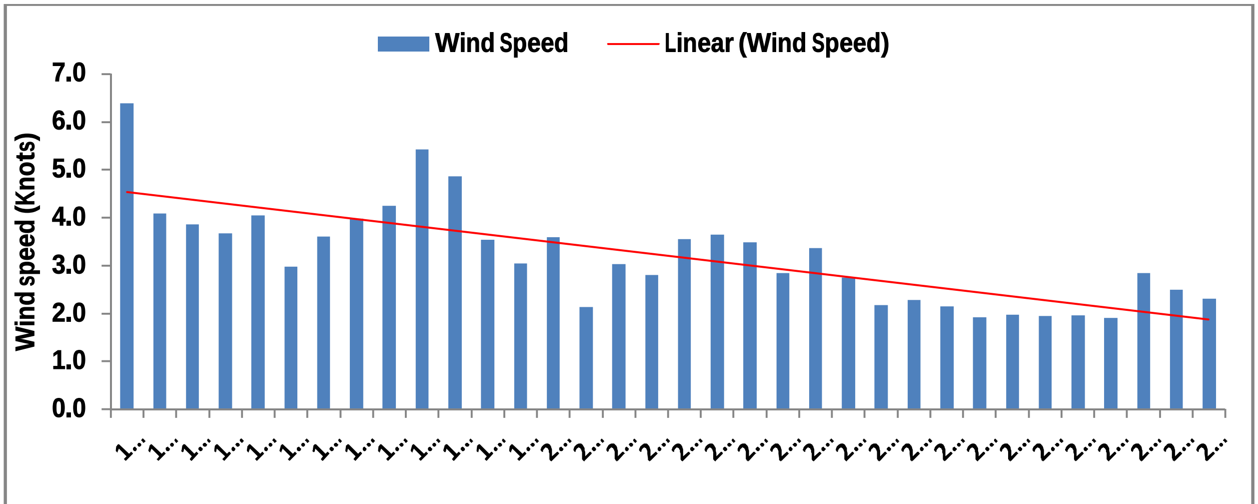

Figure 7. Wind speed variation from 1987 to 2020

Sunshine hours are the duration of sunshine on the earth's surface. It is measured through Campbell recorder. In this device a glass sphere concentrates sunlight on a card and the amount of scorching records the amount of sunlight that had fallen on it. When the sun radiation exceeds the 120 w/m^2, card starts scorching till the radiation intensity decreases. Figure 8 shows the increasing trend in average annual sunshine hours/day. Average sunshine (hours) has been increased by 0.82 hours/day. The increasing sunshine hours may cause change in temporal patterns of crop ET as the peak ET days will come earlier than its previous pattern. This will also decrease the cropping cycle increasing crop management related issues.

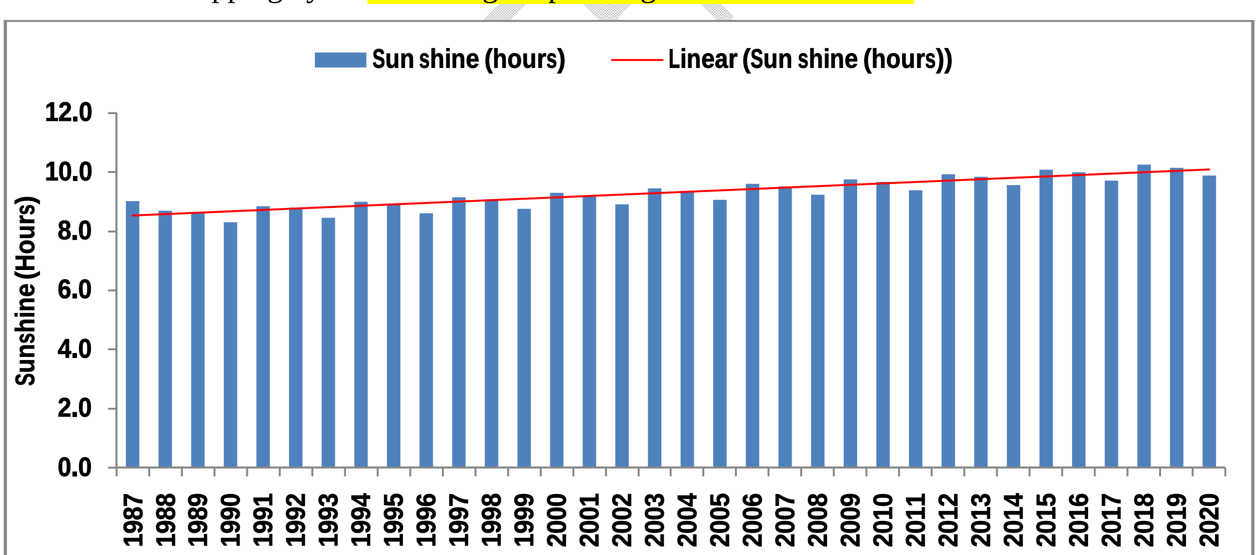

Figure 8. Sunshine hour's variation from 1987 to 2020

Figure 9 shows the decreasing trend in average annual humidity. With decrease in humidity level the crop ET increases. Since, low humidity increases the vapor pressure deficit (an indication of the dryness of the air) between the vegetative surface and air. Higher transpiration and evaporation will always need to occur to meet the evaporative demand of the air for moisture. The surrounding air's moisture demand always dictates surface to evaporate moisture to meet that demand (Irmak, 2017).

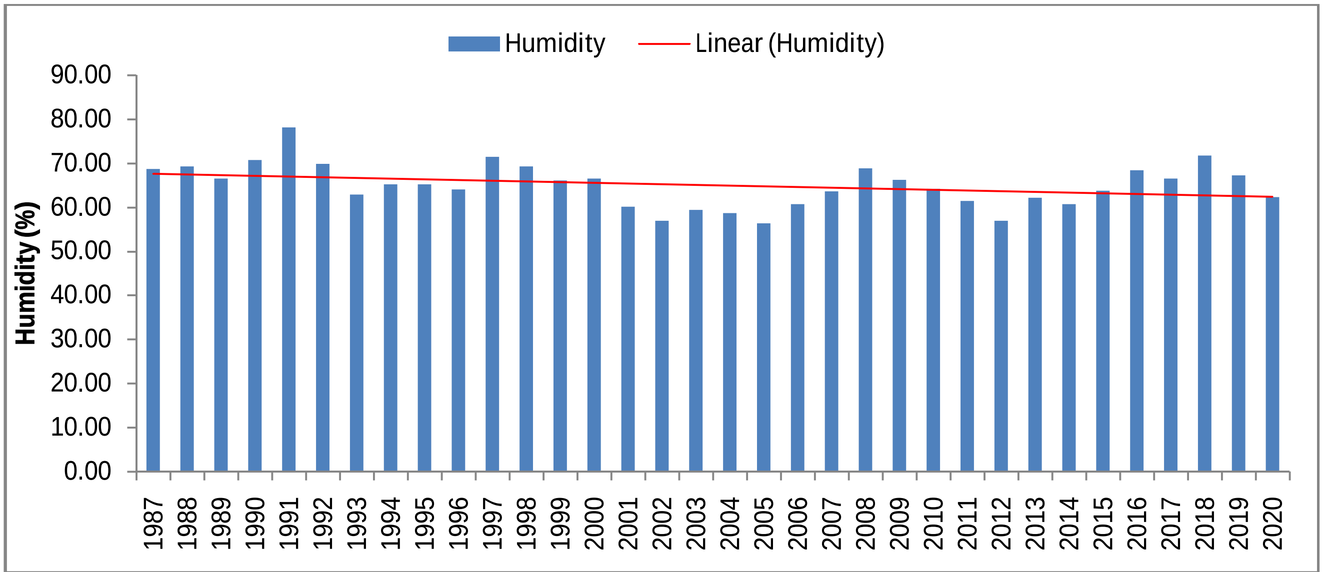

Figure 9. Humidity variation from 1987 to 2020

Figure 10 shows the decreasing trend in average annual ET_o. Mean ET_o has been decreased by 0.49 mm/day. This may be attributed to the mean daily wind speed which has decreased by 1.20 knots/day. Irmak and Mutiibwa (2010) have reported that a decrease in wind speed usually causes ET_o to decrease. Wang et al., (2012) found a decrease in ET_o (during the years 1957 to 2005) at the rate of 40.9 mm/decade and trend analysis exhibited that the reduction in ET_o was mainly dominated by the significant decrease in wind speed with high sensitivity, to a less extent, by the decrease in net radiation. Although relative humidity is one of the most sensitive variables, but its effect on ET_o they found was negligible because of its temporal constancy. They found contribution of wind speed reduction to decreased ET_o has increased from 50% to 76.1%, but net radiation, by contrast, decreased from 50% to 23.9%.

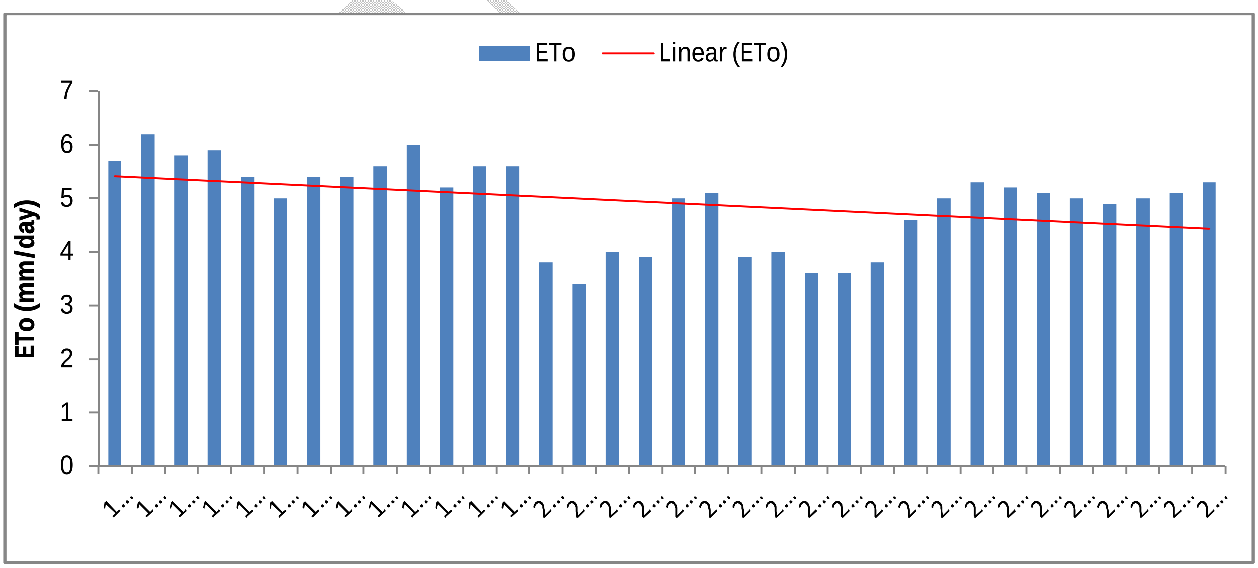

Figure 10. ET_o variation from 1987 to 2020

Figure 11 shows the decreasing trend in average evaporation rate. Evaporation rate during 1987-2003 was 6.88 mm/day which decreased to 6.26 mm/day during 2004-2020. Evaporation rate has been decreased by 0.62 mm/day. This may be attributed to the mean daily wind speed which has been decreased by 1.20 knots/day. Wang et al., (2012) found almost similar trend. They found decrease in evaporation (during the years 1957 to 2005) at the rate of 17.7 mm/decade mainly because of significant decrease in wind speed and net radiation.

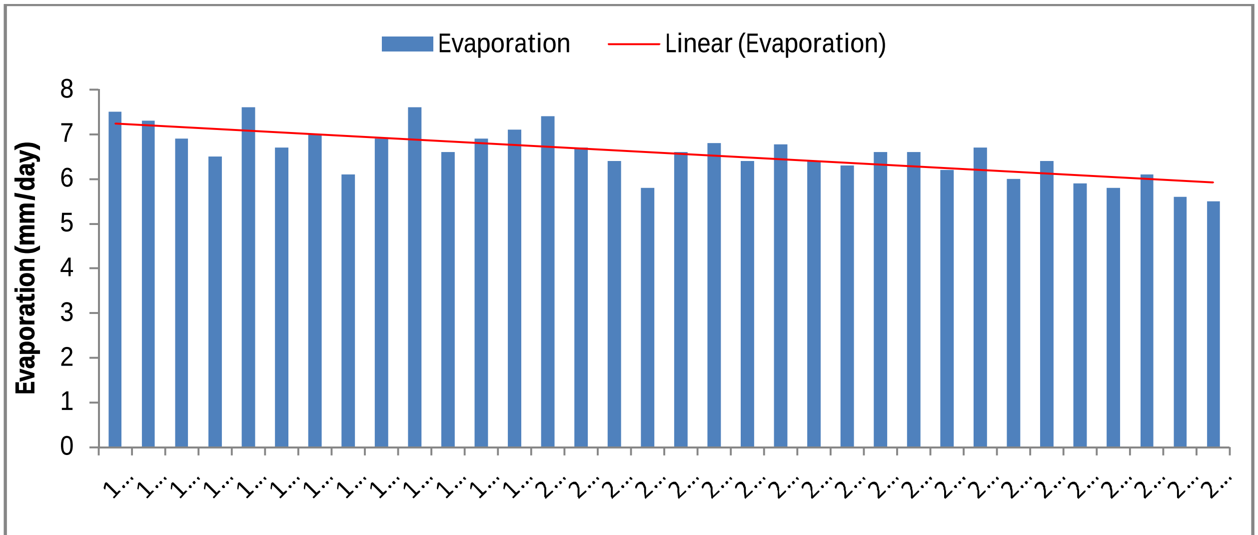

Figure 11. Evaporation rate variation from 1987 to 2020

3.2 Impact of climate change on ET and GWC to ET

Climate change has different impact patterns on crop ET. Wheat ET has increased in 2017-2021 period at 1.50 m, 2.25 m and 2.75 m WTDs under both soil types (Table 2). The rise in ET may be attributed to the increase in maximum temperature and sun shine hours during the months of peak ET requirements (December – March) (Figures 12 and 13). The increasing temperature would have provided an opportunity to transpire more from the plant leaves and tissues. With an increase in temperature, the photosynthesis rate of wheat increases (Morison, 1987) that facilitates and regulates maximally the plant transpiration (Drake *et al*., 1997). This will enhance the transpiration rate owing to that the crop ET increases (Peng *et al*., 2004).

Table 2: Wheat ET during 1986-1987 and 2017-2021

WTD (m)	**Wheat ET (mm)**			
	Sultanpur soil		**Miani soil**	
	1986-1987	**2017-2021**	**1986-87**	**2017-2021**
1.5	425d	510a	406e	470b
2.25	411e	464b	392g	430cd
2.75	390gh	431c	386h	401f
LSD = 2.4394				

Means with the same letters are not significantly different at P = 0.05

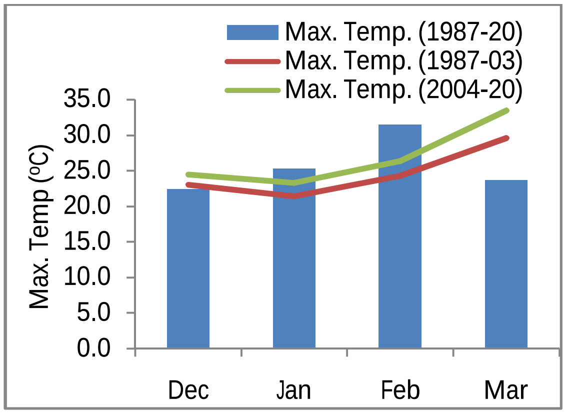

Figure 12. Max. Temperature during peak ET months

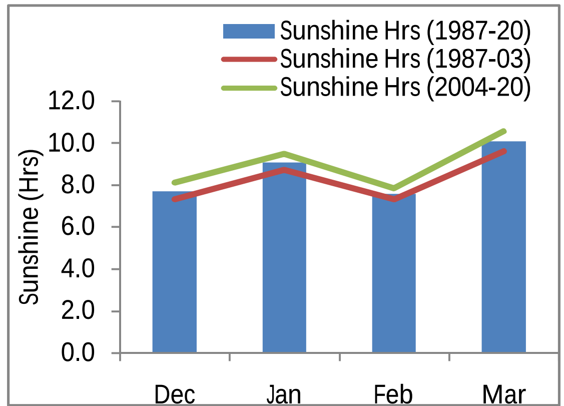

Figure 13. Sunshine hours during peak ET months

Compared to 1986-1987, ET has increased maximum during 2017-2021 at shallow (1.5 m) WTD particularly under Sultanpur soil type. This may be attributed to the (i) depth of unsaturated zone which is relatively smaller under a shallow WTD than the deeper one. Hence, under shallow WTD, capillary rise tends to supply moisture in upward direction continuously offering high opportunity for evaporation and root water uptake from the soil layers. Moreover, rising temperature and sunshine hours has further increasing effect on evaporation from the soil surface particularly under a shallow WTD where capillary fringe remains closer to the soil surface, (ii) high water holding capacity of the Sultanpur soil as 16.67 cm/m - 20.83 cm/m and lowest of Miani soil as 15 cm/m - 16.67 cm/m (NRI, 2001), owing to that Sultanpur soil holds higher amount of water. Thus, evaporation and transpiration losses in case of Sultanpur soil will be higher than in Miani soil. The increase in temperature (0.45 ^{o}C), soil characteristic and shallowness of WTD are the factors towards maximum increase in ET at shallow WTDs. The changes and the net effect of climate change on the crop ET largely depends on the interaction between these factors.

Climate change has significantly reduced the GW contribution to wheat ET (Table 3). During the cropping period of 1986-1987, it was 42-49%, 32-42% and 25-32% which have decreased to 27-29%, 12-17% and 6-8% during the recent cropping periods of 2017-2021 at 1.50 m, 2.25 m and 2.75 m WTDs under both soil types. This might be because of (i) increase in rainfall during different growth stages of wheat might have reduced the capillary rise (Figure 14), and (ii) due to the climate change (rising temperature), cropping days has decreased by 8 days (during 1986-1987 it was 125 days and during 2017-2021 it was 117 days). GW contribution to ET for those days is not part of GW contribution during 2017-2021. Therefore, it is lowest during 2017-2021 as compared to 1986-1987.

Table 3: GWC to Wheat ET during 1986-1987 and 2017-2021

WTD (m)	**GWC to Wheat ET (mm)**			
	Sultanpur soil		**Miani soil**	
	1986-1987	**2017-2021**	**1986-1987**	**2017-2021**
1.50	212a	149c	170b	127d
2.25	174b	77f	128d	50g
2.75	125d	34h	96e	23i
LSD = 2.3765				

Means with the same letters are not significantly different at P = 0.05

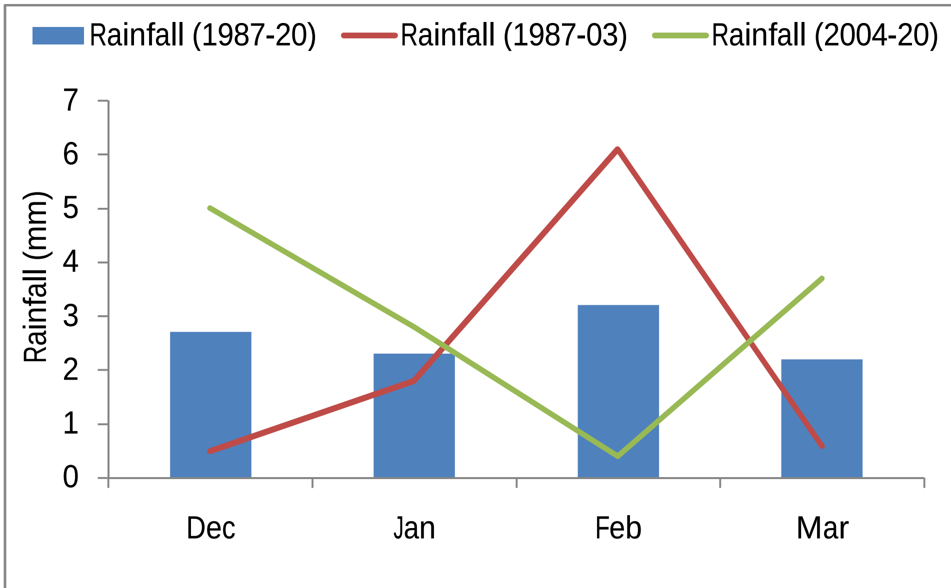

Figure 14. Rainfall during wheat peak ET months

Cotton ET has decreased in the recent cropping periods i.e. 2017-2020 at all WTDs under both soil types (Table 4). There are certain reasons behind decrease in cotton ET which are, (i) a decrease in ET_o and wind speed during the months of peak ET requirements (June to September) (Figures 15 and 16), (ii) due to the climate change (rising temperature), cropping days has decreased by 21 days (during 1987 it was 173 days and during 2017-2020 it was 152 days). The ET for those 21 days is not part of cotton ET determined during 2017-2020. Hence, ET during 2017-2020 is less than ET determined during 1987, (iii) GW contribution to crop ET is one of the main factors towards the rise in cotton ET. Higher the groundwater contribution maximum would be the crop ET. Moreover, capillary rise takes place when the soil upper layers are driers. Due to the increase in rainfall during peak ET months (June – September), about 20%-25% of the cotton ET was fulfilled by rainfall and it replenished the soil to its field capacity level. Hence, capillary rise did not taken place, resultantly cotton ET was decreased during 2017-2020 compared to that of 1987.

Table 4: Cotton ET during 1987 and 2017-2020

WTD (m)	**Cotton ET (mm)**			
	Sultanpur soil		**Miani soil**	
	1987	**2017-2020**	**1987**	**2017-2020**
1.5	899a	739d	868b	695e
2.25	908a	668f	903a	626g
2.75	861b	631g	843c	585h
LSD = 7.0775				

Means with the same letters are not significantly different at P = 0.05

Climate change has significantly reduced the GW contribution to cotton ET (Table 5). The contribution of GW towards meeting ET of cotton has significantly decreased during the recent cropping period (2017-2020) as compared to the study conducted about 35 years ago (1987) (Table 5). During the cropping period of 1987, it was 46%-49%, 43%-47% and 34%-38% which have decreased to 28%-32%, 16%-18% and 6%-8% during the cropping years of 2017-2020 at 1.50 m, 2.25 m and 2.75 m WTDs under both soil types. This decrease in GW contribution to cotton ET may possibly be because of, (i) decrease in ET_o and wind speed (Figures 15 and 16) during the peak ET months (June to September), (ii) due to the climate change (rising temperature), cropping days has decreased by 21 days (during 1987 it was 173 days and during 2017-2020 it was 152 days). The GW contribution to ET for those 21 days (82 to 96 mm at 1.50 to 2.75 m WTDs) is not part of GW contribution to cotton ET determined during 2017-2020. Hence, GW contribution during 2017-2020 is less than determined during 1987, and (iii) increase in rainfall (Figure 17) during cotton peak ET months (Jun-Sep).

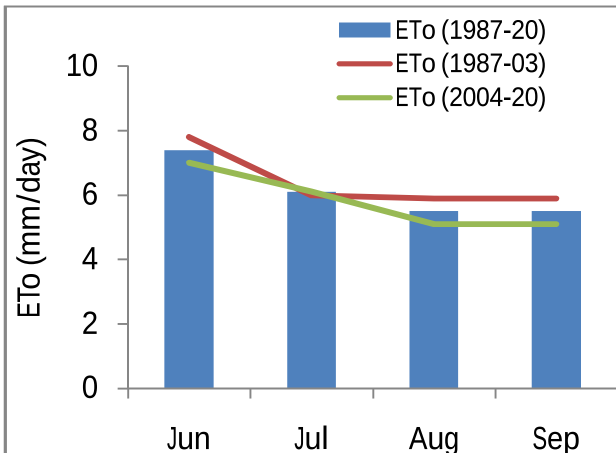

Figure 15. ET_o during peak ET months

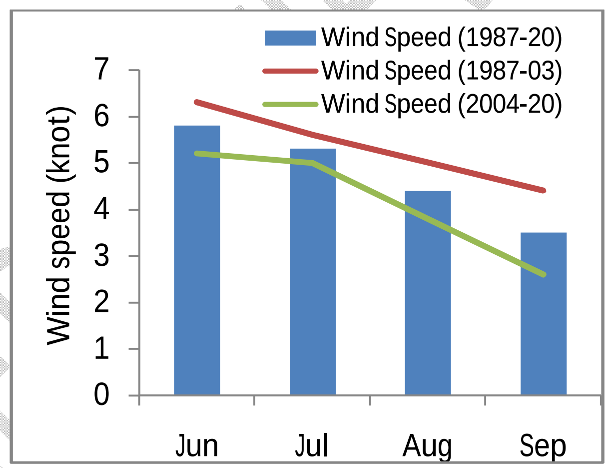

Figure 16. Wind speed during peak ET months

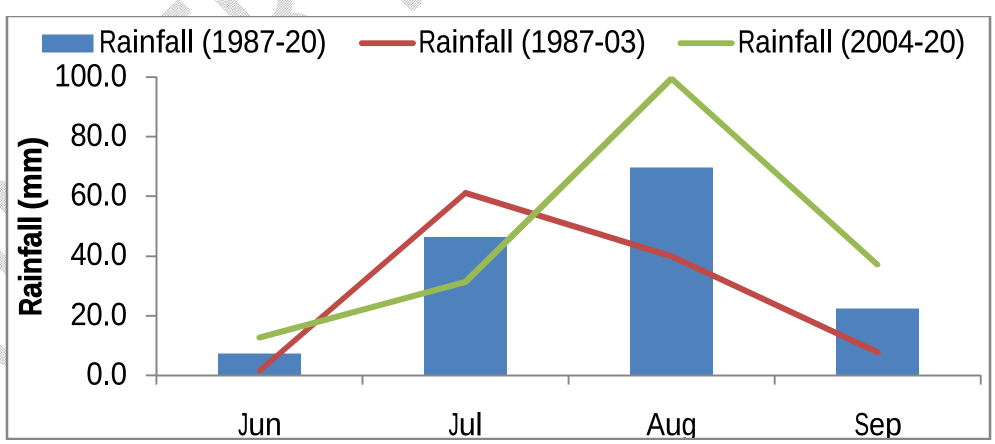

Figure 17. Rainfall during cotton peak ET (June - September)

Table 5: GWC to Cotton ET during 1987 and 2017-2020

WTD	**GWC to Cotton ET (mm)**

(m)	Sultanpur soil		Miani soil	
	1987	2017-2020	1987	2017-2020
1.5	442a	236e	398b	196f
2.25	433a	123g	389b	98h
2.75	329c	50i	287d	36i
LSD = 4.8835				

Means with the same letters are not significantly different at P = 0.05

3.3 Impact of climate change on crop yield and WUE

Climate change had no negative impact on wheat yield (latest variety NIA-Sarang) rather high yield obtained during the recent cropping periods of 2017-2021 compared to that of 1986-1987 (Figure 18). This is because NIA-Sarang wheat variety has great potential against heat stress compared to other varieties (Channa *et al.*, 2016). Wheat yield has increased 46%-53% at 1.50 m to 2.75 m WTDs under both soil types. Wheat yield is highest at shallow WTD particularly under Sultanpur soil type. This may be attributed to the ET of the crop which was satisfied from two sources (i) moisture stored in the soil in response to the irrigation or rainfall and (ii) upward movement of water from capillary zone (GW contribution). Average wheat yield in Sindh is 3342 kg/ha about 11% higher than Pakistan's (PBS, 2019). However, wheat yield during 2017-2021 under varying WTDs and soil types is 26%-37%, 35%-44% and 26%-36% higher than the average yield of Sindh, Pakistan and the world.

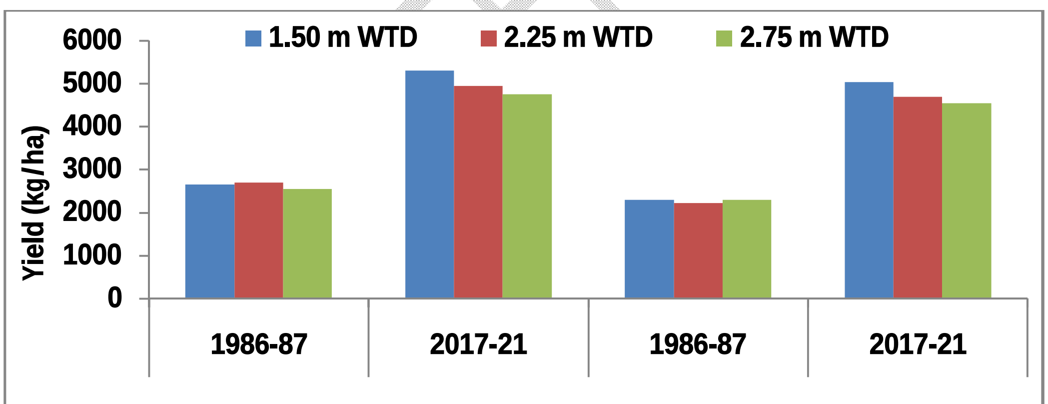

Figure 18. Wheat yield (1986-1987 and 2017-2021)

Wheat WUE is highest during 2017-2021 as compared to 1986-1987 (Figure 19). This may be attributed to the 46%-53% higher yield obtained during 2017-2021 as compared to 1986-1987. The WUE is highest at 2.75 m WTD followed by 2.25 m and 1.50 m WTDs. For Sultanpur and Miani soil types, 4%-5% WUE was higher at 2.75 m than that of 2.25 m and 1.50 m WTDs. Although, higher yield was obtained with shallow WTDs, but due to comparatively less ET, WUE was higher for deeper WTDs.

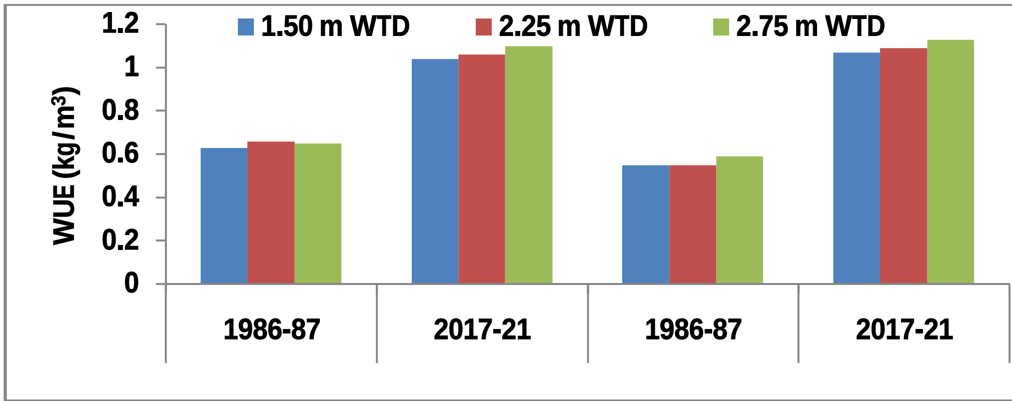

Figure 19. Wheat WUE (1986-1987 and 2017-2021

Cotton yield during 1987 was highest as compared with the four years average cotton yield during 2017-2020 (Figure 20). This may be attributed to the rainfall which severely reduced cotton yield during the cropping periods of 2019 and 2020. Rainfall of more than 25 mm particularly during the lint formation stage severely reduces the cotton yield. However, during the cropping period of 2018, there was meager rainfall (3-11 mm), owing to that highest yield of cotton was obtained as 5793-6129 kg/ha, 5210-5584 kg/ha and 4670-4832 kg/ha at 1.50 m, 2.25 m and 2.75 m WTDs under both soil types. During the cropping years of 2019 and 2020, occurrence of rainfall lost the yield of cotton to 2940-3786 kg/ha and 1863-2086 kg/ha yield was obtained at WTDs of 1.50 m to 2.75 m under both soil type. Hence, it has become imperative to grow the cotton by 1st week of April, so that the 1st highest yield bearing picking of cotton could be done before the onset of monsoon (July-September).

Cotton yield was highest at shallow WTD particularly under Sultanpur soil type. The yield was highest at WTD of 1.50 m followed by 2.25 m and lowest yield was obtained at 2.75 m WTD under both soil types. The higher yield at 1.50 m WTD may be attributed to the crop ET which was satisfied from both sources (i) moisture stored in the soil in response to the irrigation or rainfall and (ii) upward movement of water from capillary zone (GW contribution). Average cotton yield in Sindh is 1049 kg/ha about 28% higher than the Pakistan's (PBS, 2019). However, cotton yield during 2017-2020 under different WTDs and soil types was found about 70%-74%, 78%-81% and 61%-66% higher than the average yield of Sindh, Pakistan and world.

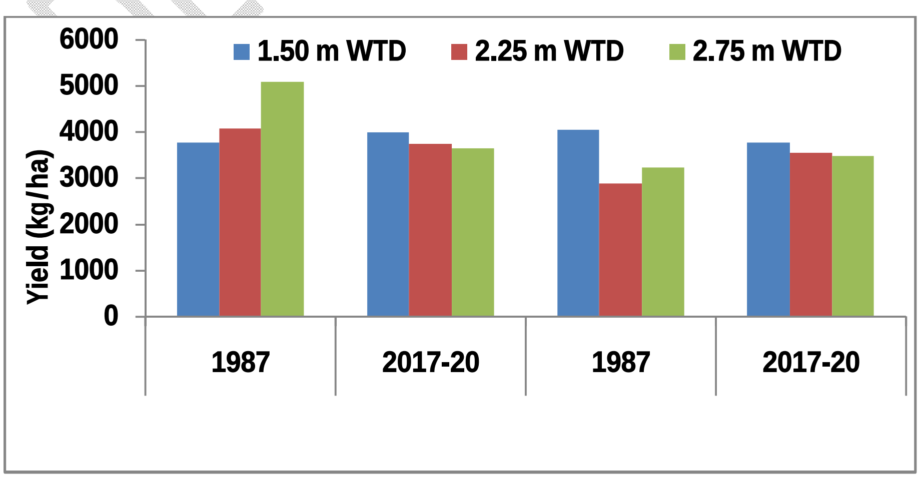

Figure 20. Cotton yield during 1987 and 2017-2020

Cotton WUE during 2017-2020 is higher than in 1987 period (Figure 21). This is because of comparatively less ET. The WUE was highest at 2.75 m followed by 2.25 m and 1.50 m WTDs. The WUE was 3%-7% and 5%-10% highest under Sultanpur and Miani soil types at 2.75 m over 2.25 m and 1.50 m WTDs. Although, higher yield was obtained at shallow WTDs, but due to comparatively less ET, WUE was higher under deeper WTDs.

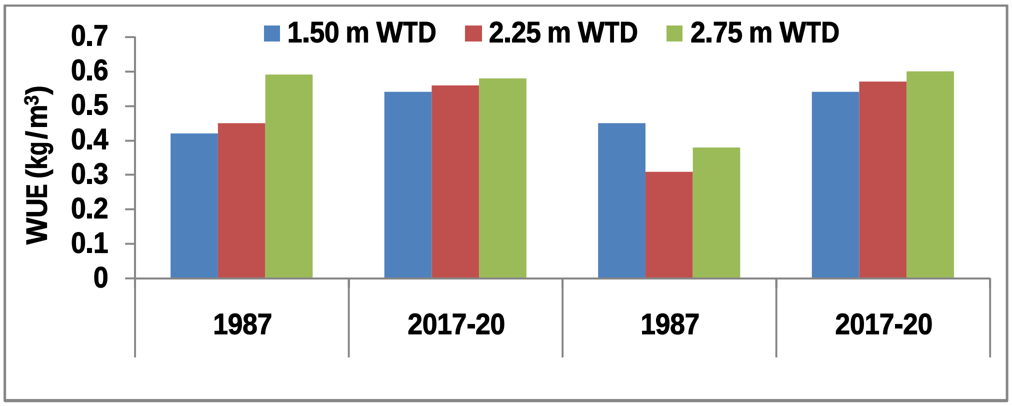

Figure 21. Cotton WUE during 1987 and 2017-2020

4. CONCLUSION

With an increase in maximum temperature coupled with sun shine hours, wheat ET has increased decreasing the cropping cycle upto 8 days. The increased wheat water demand due to climate change can put tremendous pressure on existing overstressed water resources. The decrease in sunshine hours, ET_o and wind speed during the months of peak ET are the major factors that suppressing cotton ET. GW contribution to crop ET is the main factor towards higher cotton ET. Increasing rainfall pattern will reduce the reliance on surface irrigation and will decrease the GW contribution towards meeting cotton ET (6% - 32%). Rising temperature has shortened the cotton cropping cycle by 21 days. The study demonstrates that irrigation allocation should be increased for wheat and decreased for cotton particularly in the shallow water-table areas where water table remains at 1.50 m – 2.25 m depths. Moreover, cotton crop should be cultivated by the 1st week of April, so that highest yield of cotton could be harvested before onset of monsoon.

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