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Quantifying the impacts of varying groundwater table depths on cotton evapotranspiration, yield, water use efficiency, and root zone salinity using lysimeters

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ABSTRACT

Determining the evapotranspiration (ET) of cotton as a water-intensive crop is crucial for effective irrigation planning and water management, especially in regions like Sindh province, Pakistan, where shallow groundwater table depths (WTDs) are prevalent. Despite the importance of cotton, a major cash crop in Sindh, previous studies on ET were conducted decades ago and may no longer be reliable due to ongoing climate change and the introduction of new crop varieties. Thus, we quantified cotton ET across two cropping seasons and at various WTDs (0.45, 0.60, 0.75, 1.50, 2.25, and 2.75 m). The experimental study was based on the data procured from 12 mini lysimeters and 12 large lysimeters for two years (2018 and 2019) and at two soil series. The findings revealed that cotton ET ranged from 1332 to 1437, 1114–1202, 988–1075, 781–821, 690–733, and 637–683 mm at WTDs of 0.45, 0.60, 0.75, 1.50, 2.25, and 2.75 m, respectively. WTDs from 0.45 to 0.75 m fulfilled 94–96 % of cotton ET through groundwater (GW) contribution in Sultanpur soil (silt loam) and 93–97 % in Miani soil (silty clay loam). At 1.50–2.75 m WTDs, irrigation water requirements (excluding rainfall and leaching) were 63–88 % in Sultanpur soil and 67–89 % in Miani soil. The highest yield was observed at a 1.50 m WTD, while the highest water use efficiency was identified at a 2.25 m WTD. However, soil salinity increased by 60–80 %, resulting in a 40–60 % lower cotton yield at 0.45–0.75 m WTD. Therefore, periodic flushing of salts is necessary to utilize shallow WTDs effectively. Considering GW contribution to ET when allocating water for irrigation channels and devising irrigation schedules is crucial. This approach can lead to water savings, prevent land from becoming waterlogged and saline, manage the groundwater table, and reduce the need for drainage channels and labor force for their preparation.

1. Introduction

The socioeconomic development of every nation is mainly associated with the availability of fresh water resources and its judicious use. Moreover, for the sustainability of all living beings on the earth, it is considered to be a vital natural resource (Shenkut et al., 2013). However, this vital resource is under the immense pressure due to the exponential population growth. The rising population requires a plenty of water to meet their requirements, and hence have been resulting in reduction of the per capita water availability. The issue therefore has become a matter of great concern worldwide (Yihun, 2015). Water use among different sectors is occasionally competitive in terms of quantity and quality due to its unequal distribution and availability (Tezera, 2019). Of the many freshwater users, the key contender is the agricultural sector that consumes about 93 % of the freshwater resources in Pakistan to produce food and fiber for the growing population. Therefore, special consideration needs to be given to the agricultural sector and research based on innovative scientific methods that enhance the agricultural productivity in the wake of ongoing climate change (Shenkut et al., 2013; Bashir, 2017; Gul et al., 2018; Gul et al., 2023a).

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The total share in the Indus Water of the Sindh province is 48.76 MAF (Million Acre Feet); however, during last 18 years (2000–2018), overall withdrawals remained at 39.3 MAF (GoS, 2018). In spite of the reduced canal water withdrawal, farming community in the Sindh province of Pakistan still has adopted the least efficient irrigation methods, leading to a waste of the significant amount of the freshwater, which is already scarce (Ashraf et al., 2014; Gul et al., 2023b). The lavish use of the fresh canal water resources, particularly in the agricultural sector, makes the water deficit worse in many places. This poor use of water is leading to a greater than necessary increase in fresh water withdrawals and could result in unneeded competition between various freshwater consuming sectors. This also gives rise to the water table, leading to waterlogging and waterlogging induced salinity (Bandyopadhyay and Mallick, 2003). An area where water table depth (WTD) varies between 0 and 1.50 m is regarded as waterlogged (Basharat et al., 2014). The area coverage of the shallow WTDs varies seasonally and annually; however, shallow WTDs persist, particularly in the lower parts of the Sindh province. Of the 5.50 Mha (Million hectares) irrigated area of the Sindh province, shallow WTDs cover about 55 % irrigated area (Iqbal et al., 2020). Therefore, optimizing the irrigation water use in agricultural sector is much needed particularly when shallow WTDs are predominant on a significant canal command area.

Optimizing water use in agriculture involves the proper irrigation water management by balancing the crop's need for water with the amount of water that is actually applied to the crop. However, for the proper irrigation water management, the knowledge of crop evapotranspiration (ET) and groundwater (GW) contribution to crop ET is highly important and necessary particularly in areas where shallow WTDs are prevailing. Moreover, these two variables are of the paramount importance as play a key role in the design and management of irrigation and drainage schemes (Daniel et al., 2020; Callejas et al., 2021). Crop ET is the amount of water used by a crop at any growth stage plus what evaporates from the soil surface, since the sowing up until the harvest, whenever there is no water restriction in the soil (Spano et al., 2000; Kahlown et al., 2005; Soomro et al., 2018; Gul et al., 2023b).

In the presence of WTDs, capillary water contributes to fulfill partial or entire crop ET through subsurface irrigation (Kahlown et al., 2005; Gowing et al., 2009; Karimov et al., 2014; Gul et al., 2018; Gul et al., 2023a; Gul et al., 2023b). However, the contribution varies and depends upon the crop type and its root penetration characteristics, soil types, WTDs and climatic conditions (Gul et al., 2023a; Gul et al., 2023b). Shallow WTDs ($\leq$ 2.00 m) are the potential resource that can be utilized as GW contribution or subsurface irrigation by adopting the irrigation scheduling (Gowing et al., 2009; Nosetto et al., 2009; Gul et al., 2018; Gul et al., 2023b). In that respect, Gul et al. (2018) determined that under WTDs of 0.45–0.75 m, the GW contribution to okra ET would change from 43 % to 95 % under the climatic condition of Lower Indus Basin. For banana, GW contribution to ET was 11–20 % and 10–16 % for first and second years of cropping and 7–18 % to papaya ET at 1.50–2.50 m WTDs in the Lower Indus Basin (Gul et al., 2023b). For the maize crop, Gao et al. (2017) found 35–41 % GW contribution to ET at 1–2 m WTDs. Rao et al. (2016) found the GW contribution as 26–38 % for sesame and 30–38 % for sunflower at 1.50–2.50 m WTDs. The WTDs 1.50–2.00 m are optimum depths for all major crops grown in central Punjab (Kahlown et al., 2005) and in the Lower Indus Basin (Rao et al., 2016). It is therefore obvious that GW contribution to crop ET is a significant component of water balance under shallow water table conditions. Considering GW contribution to ET when allocating water for irrigation channels and devising irrigation schedules is crucial. This approach can lead to water savings, prevent land from becoming waterlogged and saline, manage the water table, and reduce the need for drainage channels and labor force for their preparation Kahlown et al., 2005; Ayars et al., (2006); Gowing et al., 2009; Karimov et al., 2014; Gul et al., 2023b).

Cotton (*Gossypium hirsutum*) is a major fiber producing crop and is cultivated in a wide range of climatic conditions. It grows well in semi-arid climatic region. However, it can also be cultivated in tropical and subtropical regions (Tarazi et al., 2020). Among many natural crop species, it extends one of the biggest textile industries in the world. Globally, a worth of 600 billion Dollars per year is the economic impact of this crop (Ashraf et al., 2018). Pakistan ranks at 4th in cotton lint production and 7th largest cloth producing country in the world. About 60 % of the overseas earning of Pakistan comes from the cotton and its allied products. Cotton and its allied products contributes 2 % to the GDP of the country and contributes 10 % to the agriculture value added (Bakhsh et al., 2019; Sial et al., 2014; Shuli et al., 2018). About 1.7 million farmers are engaged in cultivation of cotton each year in Pakistan (Shuli et al., 2018). Cotton is one of the major crops in the fiber chain system and with the rapid growth of the population; its importance is becoming prodigious. Therefore, increasing per hectare cotton yield is becoming the top priorities of different organizations and agricultural firms (Tezera, 2019). However, there is a lack of site and crop specific data needed for planning and management of irrigated cotton crop under shallow water table conditions. Thus, determining cotton ET and the share of shallow GW contribution to its ET are much required in a changing climate. With the aspirations discussed above, the current study was designed for growing cotton crop in the cropping seasons of 2018 and 2019 at 0.45, 0.60, 0.75, 1.50, 2.25 and 2.75 m WTDs in Sultanpur soil series (silt loam) and Miani soil series (silty clay loam). To carry out such study in an open field is intricate and not trustworthy, given that, many causative factors will be involved; therefore, obtaining accurate data will also be difficult. As lysimeter is a perfect model to replicate the desired scenarios and allow an appropriate solution of the problem, this study was carried out in a lysimeter experimental site.

2. Materials and methods

2.1. Experimental site

Two years lysimeteric studies were carried out on the cotton crop at the Drainage and Reclamation Institute of Pakistan (DRIP), Tando Jam, Sindh, Pakistan (Fig. 1). The study area falls under semi-arid climate conditions. Annual maximum temperature varies from 22.36 to 39.35 °C, whereas, minimum temperature varies from 10.76 to 28.95 °C. Humidity peaks in the months from July to September (72–76 %). Annual precipitation in the study area is 166 mm with unequal distribution over different months. The mean sunshine hours are 9.30 hr/day, making the region favorable for the cultivation of many crops. Mean daily reference evapotranspiration (ET_o) varies from 2.59 to 7.64 mm/day with an average value of 4.93 mm/day (Gul et al., 2023a).

2.2. Experimental design

The experiments were conducted in accordance with the principles of Randomized Complete Block Design – Factorial using twenty-four lysimeters with two factors and twelve treatments (Gul et al., 2023a; Gul et al., 2023b). The factors were the WTDs and soil types (S). Six different levels of water table were maintained with two soil types. Each WTD was replicated two times for each soil type. The depths of water table maintained were 0.45, 0.60, 0.75, 1.50, 2.25 and 2.75 m. The soil types were S1: Sultanpur soil series (Silt loam texture) and S2: Miani soil series (Silty clay loam texture). Twelve circular type mini lysimeters were used to maintain the shallow WTDs at 0.45, 0.60 and 0.75 m for the two soil types with two replications. For the deeper WTDs maintained at 1.50 m, 2.25 m and 2.75 m, twelve square shaped larger sized lysimeters were used. The treatments were arranged as T1 = WTD1 ×S1, T2 = WTD2 ×S1, T3 = WTD3 ×S1, T4 = WTD4 ×S1, T5 = WTD5 ×S1, T6 =WTD6 ×S1, T7 = WTD1 ×S2, T8 = WTD2 ×S2, T9 = WTD3 ×S2, T10 = WTD4 ×S2, T11 = WTD5 ×S2 and T12 = WTD6 ×S2.

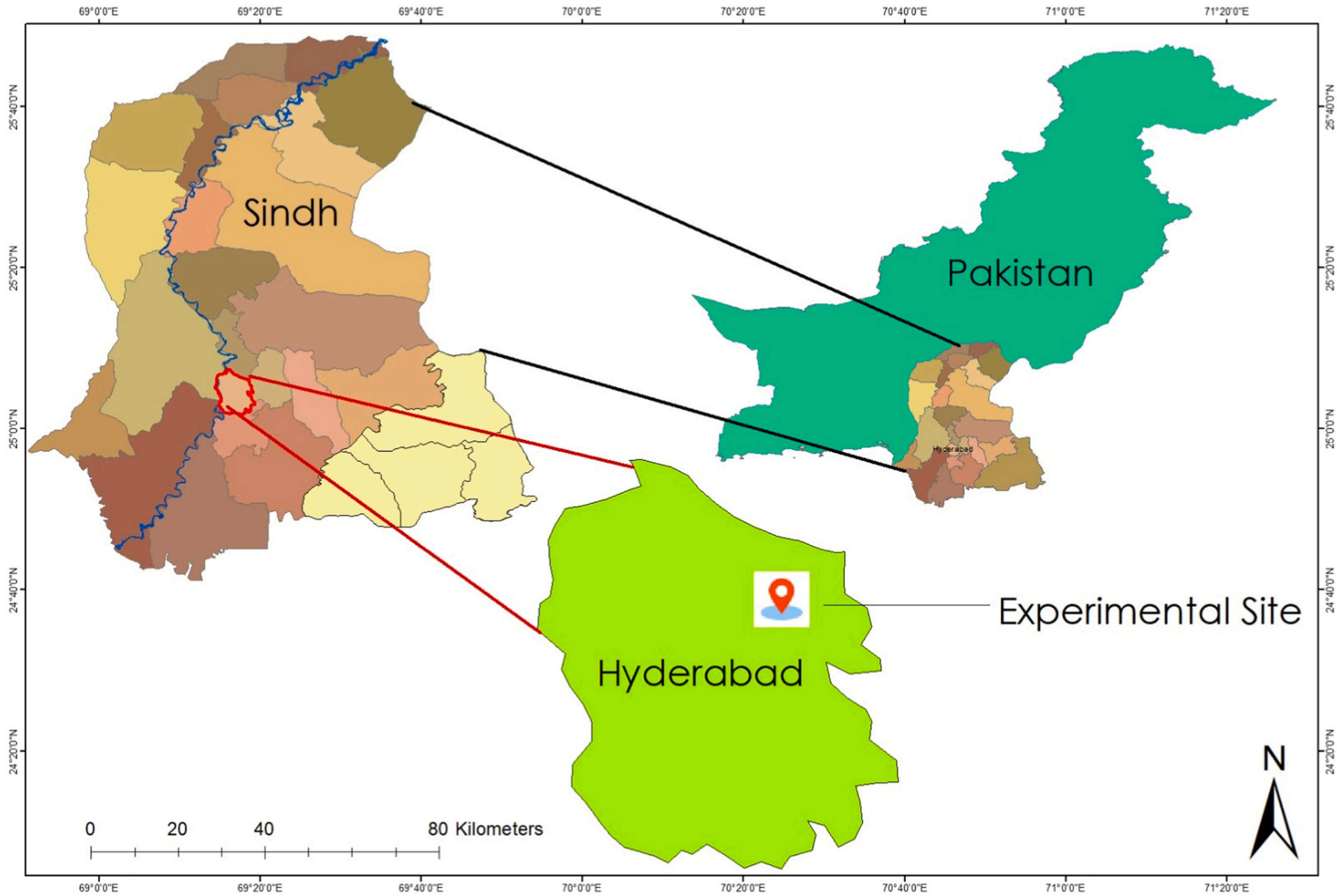

Fig. 1. The geographical location of the experimental site on the Sindh province and Pakistan's map.

2.3. Larger lysimeters

Twelve large drainage type and square shaped lysimeters were constructed in 1985 at DRIP, Tando Jam. These leakage proof lysimeters are made up of reinforced cement concrete (RCC). The operational dimension of each lysimeter is 3.05 (length), 3.05 (width) and 5.13 m (depth). The lysimeters are constructed into two rows. Each row consists of six lysimeters. South panel of six lysimeters is filled with Sultanpur soil series (silt loam) and north panel of six lysimeters is filled with Miani soil series (silty clay loam). Both of these soil series are available at DRIP, Tando Jam. Both of these soil series are identified, located, and mapped in the detailed soil survey report of DRIP campus Tando jam (Shaikh and Yaseen, 1980).

In each lysimeter, soil material is filled up to a depth of 2.40 m. The soil material underneath in each lysimeter is filled with 2.13 m layer of river sand, 0.30 m gravel and 0.30 m spawls. Before filling of soil material, river sand, gravel, and spawls, a scale was marked on inner side of the walls of each of the lysimeters to know the thickness of the soil layers to be filled in. A vertical cut was given to each soil series in the field by excavating 2.50 m deep pits. The dry bulk density of both of the soil series in the field was determined layer-wise with a depth increment of 0.15 up to 2.40 m depth. From each soil layer of the soil series, only 0.15 m soil was used for pressing at a time until the whole layer was completed. Whenever any clods were found in the layers, the soil was pulverized and then filled in lysimeters. Each 0.15 m soil layer was rammed with wooden blocks of 0.30 × 0.30 × 0.30 m to attain the desired dry bulk density as was found in the natural conditions. Each lysimeter was left unfilled as 0.15 m from top of the lysimeters for irrigation purpose. An inner wall of 0.30 m thickness was provided between the two lysimeters to separate a lysimeter from other one.

Between the two rows of the lysimeters, a buffer of 4.00 m is provided, which is also roof of the observation chamber. The roof of the observation chamber is 1.00 m lower than the top of the lysimeter chamber. Roof of the observation chamber was also filled with the soil without distinguishing the soil layer. Soil on the roof is filled about 0.85 and 0.15 m is left unfilled for irrigation purpose. Besides, all around the lysimeters, a 3.00 m side berm is provided with equal level of soils in the lysimeters and top of the roof. This is done to provide a patch for the same crop cultivation, creating a natural environment to avid the oasis effect. The berms are also provided with small earthen dikes to control irrigation water. Each lysimeter is supported with filter screens, drainage outlet, and water feeding arrangement. To maintain the desired WTDs and measure GW contribution to crop ET, graduated Marriotte bottles were installed on all of the twelve lysimeters. Three outlets were established at the bottom of each of the lysimeters. Each one is used to take out drainage surplus, inducing water in the lysimeter through Marriotte bottle to maintain desired WTD and to measure head of water through a pressure gauge. Figs. 2–4 show the schematic diagram of the large lysimeters, diagram of the equipment installed at large lysimeters and soil profile filled in each large lysimeter.

2.4. Mini lysimeters

The mini lysimeters comprise of circular Reinforced Cement Concrete (RCC) pipe. These were installed in 1992 at the DRIP campus. These are non-weighing/drainage type, each having an internal diameter of 0.45 and 1.20 m deep. In the mini lysimeteric setup, there lies a passage between two rows of the chambers. The passage width is about 1.46 m, which is situated at about 1.52 m below the ground surface. For monitoring and installing of instruments, a staircase is mounted, which

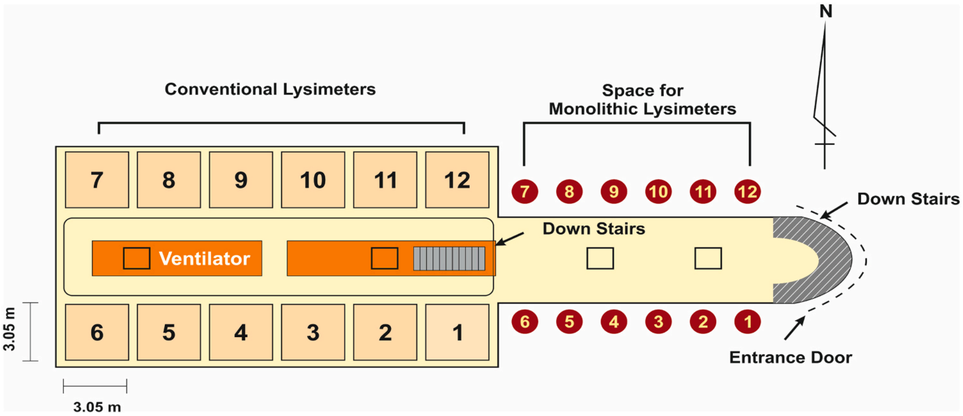

Fig. 2. Schematic diagram of the large lysimeters.

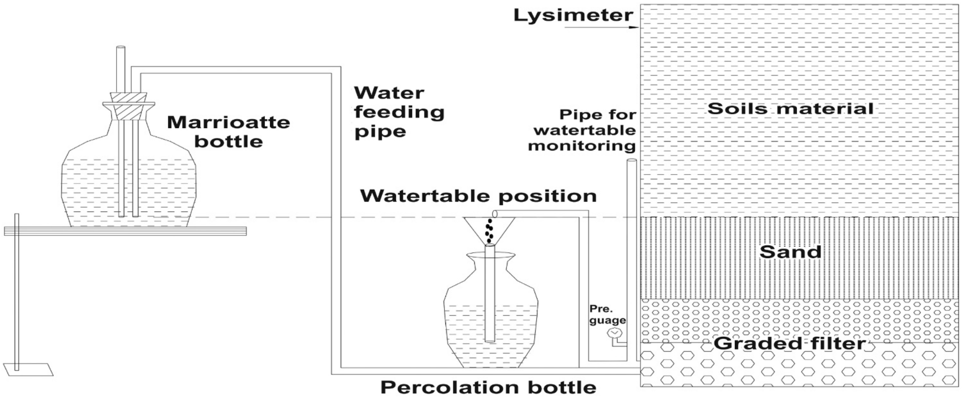

Fig. 3. Diagram of the equipment installed at large lysimeters.

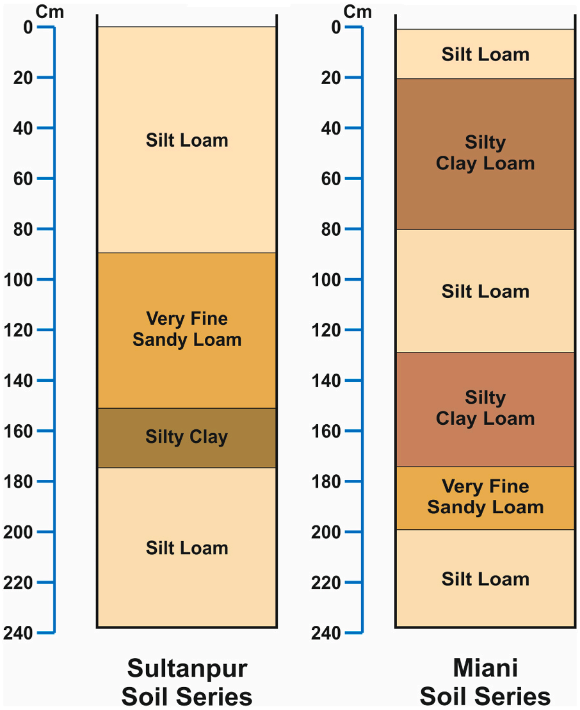

Fig. 4. Soil profile filled in each large lysimeter.

leads from the ground surface towards the base of the passage. In each lysimeter chamber, an individual piezometer of 2.54 cm diameter is installed to monitor the WTD.

Six mini lysimeters are filled with Sultanpur soil series (silt loam textured) and other six mini lysimeters are filled with Miani soil series (silty clay loam textured). To maintain the water table at varying shallow depths, twelve Marriotte bottles were installed on all 12 mini lysimeters. A single outlet was installed at the bottom of each mini lysimeter. However, with this outlet, a junction of three outlets was set. Two of them were used to take out drainage surplus and one to induce water in the lysimeter through Marriotte bottle to maintain desired WTD.

2.5. Maintenance of water table depth

The WTDs in larger lysimeters were maintained through graduated Mariotte bottles each of 52 liter capacity, whereas Mariotte bottles made-up of plastic with a 20 liters storage capacity used in mini lysimeters. Each Mariotte bottle for larger lysimeters was provided with a double hole rubber bung for capping its mouth, whereas wooden bung used for mini lysimeters. For Mariotte bottles used in larger lysimeters, two silver tubes were passed through the holes of the bung up to the inner end of the Mariotte bottle. The upper end of one silver tube (6.75 mm) opened in the atmosphere and the second one (10 mm) connected to the water feeding PVC rubber pipe (12.7 mm) attached at the bottom of lysimeters through the gate valves. For Mariotte bottles used in mini lysimeters, one silver tube and one PVC tube were passed through the holes of the wooden bung up to the inner end of the Mariotte bottle. The upper end of one silver tube (6.75 mm) opened in the atmosphere and the PVC tube (10 mm) connected to the water feeding

PVC rubber pipe (12.7 mm) attached with the outlet at the bottom of lysimeters. The bottom of the Mariotte bottles was positioned in line with the designed WTD (Fig. 5a-b). Thereafter, water from the Mariotte bottle was supplied into the lysimeter to raise and maintain the WTDs in each lysimeter. Due to soil water deficits at a certain level, capillary force exerts a negative pressure, which in turn, GW flows towards the upward direction. As a result, WTD in lysimeters could decrease. As Marriotte bottles are connected with the lysimeters, water will flow from bottle towards lysimeters to maintain the water table in its previous level. In this way, any drop in the water table in a lysimeter induced the water flow from the Mariotte bottle towards the lysimeter to maintain its designed water table. The water level declined in Mariotte bottles was compensated by refilling the bottles daily to their previous levels, maintaining even the minimum volume of water in the lysimeters. This procedure enabled estimation of the GW contribution to meet the crop ET through subsurface irrigation.

2.6. *Sowing of seeds*

Bacillus thuringiensis (Bt) cotton variety ''FH- 901'' was released during the year 2000 by Cotton Research Institute (CRI), Ayub Agricultural Research Institute (AARI), Faisalabad (Rahman et al., 2014). The Bt cotton variety (FH- 901) is insect resistance and has ability to resist against the heat stress as well. In the Sindh province of Pakistan, Bt seeds are grown on 80 % of cultivated cotton areas, primarily in district Hyderabad, Nawabshah, Sanghar, MirpurKhas, Tando Allah Yar, Umer Kot, Matiari, Khairpur, Sukkur, and Nowshero Feroze (Ahsan and Altaf, 2009). In the larger lysimeters, delinted seed of cotton (FH-901) was sown through hand driller at a seed rate of 12 kg/ha, keeping the row spacing of 0.75 m. In case of mini lysimeters, seeds were scattered on the soil surface and then covered with 1–1.5 cm soil depth. Buffer area of mini lysimeters was also cultivated with the same crop. After applying the second irrigation, the thinning of germinated plants was carried out to maintain the plant spacing of 20 cm as shown in Fig. 5c (Awan et al., 2011).

2.7. *Irrigation scheduling in lysimeters*

Crops grown at $\leq$ 1.00 WTDs do not need surface irrigation, as all of their ET can be met from the shallow water table. However, the ET of the crops cultivated at WTDs $>$ 1.00 m are fulfilled from both sources, i.e., surface irrigation and GW contribution (Kahlown et al., 2005; Gowing et al., 2009; Karimov et al., 2014; Gul et al., 2018; Gul et al., 2023b). There was no need of irrigation water to cotton crop grown at shallow WTDs (0.45–0.75 m), except for the soaking dose. All of its ET was met by the GW contribution. However, ET of cotton crop cultivated at WTDs varying from 1.50 to 2.75 m was met with both surface water and GW contribution. Hence, both facilities were arranged in this experiment. Irrigation was applied when the available soil moisture in the crop-effective root zone was depleted by 50–55 %. Available soil moisture is the difference between field capacity and wilting point. The average field capacity and wilting point for both soil types were 42 % and 7 %, respectively, with a dry bulk density of 1.4 g/cm^3. These soil properties were determined in the Soil Physics Laboratory of PCRWR and are comparable with those reported by Grewal et al. (1990), Saxton and Rawls (2006), Yost (2016), Malik et al., (2022), and Malik and Ashraf (2023). The available soil water with these soil properties is 35 %. When 50–55 % of the available water was depleted (moisture remained at 16–18 %), the next irrigation was applied. The available soil moisture was determined through the gravimetric technique. The

Fig. 5. a) Marriotte bottles installed for water table maintenance in larger lysimeter; b) Marriotte bottles installed for water table maintenance in mini lysimeter; c) Thinning of cotton plants in larger lysimeters; d) Irrigation application to cotton in large lysimeters; and e) Picking of cotton fiber from cotton plants in larger lysimeters; and f) Thinning of cotton plants in mini lysimeters.

root depth of 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 collected from 0 to 0.15 m, 0.15–0.30 m and 0.30–0.45 m depths. The sampling started after 4–7 days of irrigation application so that soil moisture dropped from the field capacity level. The sampling continued until the next irrigation was due. The results of these samples were averaged and checked to determine whether the soil moisture reached the required level. Soil at the available water level stores approximately 158 mm of water in the 0.45 m root zone. It has been reported by Allen et al. (1998) that soil moisture depletion is equivalent to the net irrigation requirement (excluding rainfall and leaching requirement); therefore, at a depletion of 50–55 % of the available water, 70–75 mm of irrigation water was applied to all twelve larger lysimeters (no irrigation was required for cotton except soaking dose in mini lysimeters as its water need was met by GW contribution). There was no need to consider the leaching requirement with irrigation water at 1.50–2.75 m WTDs, since soil EC was within the permissible limit ($\leq$4 dS/m). The soil salinity increased at 0.45–0.75 m WTDs after two cropping seasons of 2018 and 2019; however, at the shallower WTDs (0.45–0.75 m), all of cotton ET was met by the GW contribution through capillary rise as the WTD was closure to the soil surface. Hence, at these WTDs, irrigation water was not applied to cotton crop and therefore leaching requirement was not considered. Overall, 10 irrigations were applied to cotton crop during the cropping period of 2018 (1st irrigation was applied on May 11, 2018 and 10th on September 17, 2018) and 8 irrigations in 2019 (1st irrigation was applied on May 03, 2019 and 8th on September 08, 2019) at 1.50–2.75 m WTDs. The canal water was collected in a reservoir and then pumped to an overhead water tank (2 m high), and irrigation was applied to lysimeters through a pipeline. A water meter was fitted on the main inflow pipeline to measure the amount of water applied.

2.8. Fertilizer application

The crop fertilizer requirement varies with the crop variety and concentration of nutrients already available in the soil. However, a 200–57–62 kg/ha NPK was applied to the cotton crop (Ali et al., 2003). During the preparation of lysimetric 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 quantity and applied during the 1st and 3rd irrigations. In case of mini lysimteres, all of the P and K were applied once as basal dose, while N was dissolved in tank and applied through foliar spray.

2.9. Yield and water use efficiency (WUE)

After 50–60 days of germination, the cotton plants start bearing the flowers. Within a seven-day period, flower dries and falls on the ground surface and exposes the boll development. Four weeks are required from flowering to fiber picking from the boll. It is important to explain that after starting flowering, cotton develops flowers and bolls, which produces the fibers simultaneously. Even during the last fiber picking, some of the green bolls leftovers remain on the plants. During each cotton cropping year, 3–4 times cotton fiber was picked (Fig. 5e). Initially, the yield was measured for each lysimeters and converted to kilogram per hectare (kg/ha). Water use efficiency (WUE) is the ratio of crop production to ET. It is calculated as the yield (kg) per unit of ET (m^3). WUE is a simple estimate to measure how accurately water has been used for crop production. Any effort that tends to increase crop yield or reduce the amount of water needed without reducing the crop yield, increases the WUE (Ashraf and Saeed, 2006; Gul et al., 2023b). The yield (kg) of crops under each treatment was divided by cotton ET (m^3) to determine WUE of crops (kg/m^3).

2.10. Agronomic parameters

To record the agronomic parameters of cotton, five plants were selected and tagged (attaching of stick and card to plant for observation purpose). The agronomic parameter of cotton such as sympodial branches (yield bearing), plant height, dry biomass and bolls/plant was measured and recorded. The plant height was measured using a stick attached with the soft measuring tape.

2.11. Soil analysis

The use of shallow WTDs needs appropriate management; otherwise, it may damage the soil health. Thus, the overarching goal of using shallow WTDs may not serve. To assess any change in soil properties, the soil samples were collected before execution of the study in April 2018 and at the end of study in March 2020. It is worthy to mention that wheat was cultivated after last picking of cotton fiber during both growing seasons. However, data and result for wheat are not shown in the article as they are beyond the scope of this research. In total, 144 soil samples were collected. The soil samples were taken from all of the twelve lysimeters at depths varying between 0 and 0.15, 0.15–0.30, and 0.30–0.60 m. The collected samples were packed in polythene bags and label card was kept in the bags as they could easily be identified. The chemical properties of the soil that were examined during the study include EC (electrical conductivity of soil), pH, Ca^{2+}, Mg^{2+}, Na^{+}, SAR, and ESP. The soil pH and EC are determined by 1:2 soil water extract ratio method (US Salinity Laboratory Staff, 1954). Soluble Ca^{2+} and Mg^{2+} are determined by the EDTA titration method (manual titration by using glass burette, pipette, and beaker), while Na^{+} is analyzed by the EEL-Flame photometer (Fresenius et al., 1988). The formulations for computation of the Sodium Adsorption Ratio (SAR) and the Exchangeable Sodium Percentage (ESP) are presented below:

$$\mathrm{SAR} = \frac{Na^{+}}{\sqrt{\frac{Ca^{2+}+Mg^{2+}}{2}}} \tag{1}$$

$$\mathrm{ESP} = \frac{100\ (-0.0126 + 0.01475 \times \mathrm{SAR})}{1 + (-0.0126 + 0.01475 \times \mathrm{SAR})} \tag{2}$$

2.12. Determination of crop evapotranspiration (ET)

Crop ET is the amount of water used by a crop at any growth stage plus what evaporates from the soil surface, since the sowing up until the harvest, whenever there is no water restriction in the soil (Spano et al., 2000; Kahlown et al., 2005; Soomro et al., 2018; Gul et al., 2023b). The crop ET was calculated using water balance equation given below (Kahlown et al., 2005; Ashraf et al., 2018; Gul et al., 2023a; Gul et al., 2023b):

$$\mathrm{ET} = I + S + R - D \pm \mathrm{SMS} \tag{3}$$

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

2.13. 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 the analysis of variance (ANOVA) procedures at 95 % confidence interval (α=0.05). All statistical analysis was conducted using the Statistix Software Package Version 8.1.

3. Results and discussion

3.1. Evapotranspiration (ET)

Cotton ET found to be 683–821 mm in Sultanpur soil series, but 637–781 mm in Miani soil series at 1.50–2.75 m WTDs, respectively (Fig. 6). Cotton ET determined by Rao et al. (2016) under the climatic conditions of Lower Indus Basin (Lower Sindh) is 10–24 % higher than those of determined in recent period (2018–2019). This may be attributed to (i) the varietal difference as NIAB-78 variety cultivated by Rao et al. (2016) and FH- 901 in recent cropping period; and (ii) number of days the crop was in the field i.e. 173 days taken in Rao et al. (2016) and 161 days in the current study. Hence ET for the reduced 12 days is not the part of ET in recent periods and GW contribution for the reduced 12 days is not part of the ET during the recent periods.

There is no further work conducted on cotton crop in Pakistan and in the world through lysimeters at varying WTDs. However, many researchers have estimated cotton ET through the cropping models. Zhang and Li (2022) found cotton ET via the Hydrus 1D model in China as 567–755 mm at 1–4.00 m WTDs, respectively. These values are much lower than those found in the current study, which can be possibly associated with (i) the use of old phenological data of the crop studied about 8 years ago (2010 and 2011); (ii) the variation in climatic conditions and; (iii) variation in ET due to the model used. Qureshi et al. (2011) showed the ET of cotton as 250 mm at 2.00 m WTD using the SWAP model under the climatic conditions of Sardarya, Uzbekistan. The results of the current study are much higher than those reported by Qureshi et al. (2011). Again, this may possibly be due to the fact that models' calculations are based on numerical methods, thus not reflecting the impact of physical weather conditions.

Cotton ET was estimated 1075–1437 mm in the Sultanpur soil series and 988–1332 mm in Miani soil at 0.45–0.75 m WTDs, respectively, which are much higher than those estimated at 1.50–2.75 m WTDs. This can be attributed to the GW contribution to meet the cotton ET, which was much higher under the shallow WTDs. The thickness of vadose zone (unsaturated zone) is relatively smaller under a shallow WTD than the deeper one. Hence, under shallow WTD, capillary rise tends to supply moisture in an upward direction continuously, offering a higher opportunity for evaporation and root water uptake from the soil layers as the GW contribution to ET was found to be the highest under shallow WTDs. Moreover, at shallowest WTDs of 0.45–0.75 m, plant utilizes less water to meet transpiration and a significant amount of water from the soil surface is lost as evaporation (Gul et al., 2018). In the areas where WTDs are shallower, use of shallower WTDs is beneficial for crop water use and it is essential to take into account the GW contribution to ET during the allocation of water for irrigation channels and the development of irrigation schedules. This practice can result in conserving water, averting waterlogging and salinity in the land, effectively managing the water table, and diminishing the necessity for drainage channels and associated labor efforts.

Cotton ET is 46–105 mm higher in the Sultanpur soil series than that of Miani at 0.45–2.75 m WTDs, respectively. This may be associated with the high-water holding capacity of the Sultanpur soil series (16.67–20.83 cm/m) as compared to the Miani soli series (15–16.67 cm/m) (NRI, 2001). High-water holding capacity indicates that the Sultanpur soil series shows the highest porosity as opposed to the Miani soil series (NRI, 2001; Gul et al., 2023a; Gul et al., 2023b), thereby facilitating a more capillary rise in the Sultanpur soil series than in Miani, which in turn, a higher ET under shallow WTD is expected.

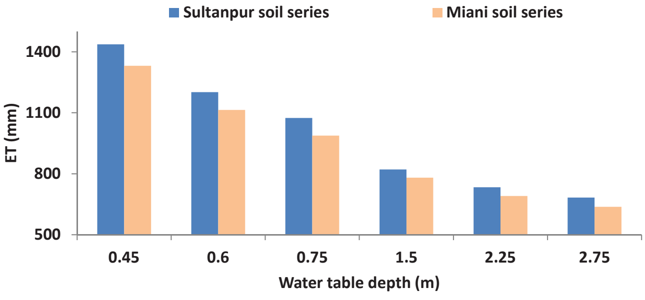

Fig. 6. The estimated lysimetric ET of cotton.

Temporal variation in cotton ET at different WTDs is given in Fig. 7. At 0.45–0.75 m WTDs, the ET increased starting from April (sowing time), declined in July, but increased to its peak in August and then again declined in September (last fiber picking). Temporal variation in cotton ET at 1.50–2.75 m WTDs followed the similar pattern of 0.45–0.75 m WTDs, except it did not decline in July. This difference in temporal variation in ET between WTDs of 0.45–0.75 m and 1.50–2.75 m may be attributed to the low sunshine hours during the month of July (8.76 hrs/day in June 2018; 9.99 hrs/day in June 2019; 6.47 hrs/day in July 2018; 7.54 hrs/day in July 2019; 6.47 hrs/day in August 2018; and 7.86 hrs/day in August 2019 measured through Campbell stocks sunshine hours) and frequent rainfall during the month of July of 2019 (18.33 mm on July 22, 2019; 106.4 mm on July 29, 2019; and 2.50 mm on July 30, 2019), which led to reduction in the evaporation from the soil surface and transpiration from the plants leaves and tissues, and ultimately reduced the GW contribution at 0.45–0.75 m WTDs. Consequently, the cotton ET decreased in July at 0.45–0.75 m WTDs. The increase in ET from April and onward may be ascribed to (i) small canopy and flowering stage during April, May and June, which might have resulted in a high evaporation from the bare soil surface and maximum transpiration from the plants leaves and tissues, and (ii) to fully developed stage of the crop during the month of August (plants produced flowers, bolls and fibers simultaneously), thus resulting in a maximum evaporation and transpiration.

3.2. Groundwater (GW) contribution to evapotranspiration (ET)

The contribution of GW to meet cotton ET varied for different WTDs and soil types. It was the highest under the shallow WTDs, where a major fraction of the cotton ET was fulfilled. This may be attributed to the height of vadose zone (unsaturated zone), which is relatively smaller under a shallow WTD as compared to a deeper one. Hence, under the shallow WTD, capillary rise tends to supply moisture in an upward direction continuously, offering a higher opportunity for evaporation and root water uptake from the soil layers. The GW contribution to the ET was found to be the highest in case of Sultanpur soil than that of the Miani soil series. The contribution of GW is largely dependent on the physical and hydraulic soil properties, including soil porosity and particle sorting (Gul et al., 2023b). High-water holding capacity of Sultanpur soil (16.67–20.83 cm/m) as compared to Miani (15–16.67 cm/m) indicates that the Sultanpur soil series shows the highest porosity as opposed to the Miani soil series (NRI, 2001; Gul et al., 2023a; Gul et al., 2023b), thereby facilitating a more capillary rise in the Sultanpur soil series than in Miani.

The GW contribution to the cotton ET varied from 1402 to 1015 mm in the Sultanpur soil series and from 1289 to 918 mm in the Miani soil series at 0.45–0.75 m WTDs, respectively (Fig. 8). Likewise, at 1.50–2.75 m WTDs, it varied from 307 to 79 mm in the Sultanpur soil series and from 257 to 67 mm in the Miani soil series. At WTDs between 0.45 and 0.75 m, 94–96 % of the ET of cotton fulfilled via the GW contribution in the Sultanpur soil series and 93–97 % in the Miani soil series. This implies that the shallow WTDs serves as a potential subsurface irrigation resource for cotton as an alternative for surface irrigation supply when cotton is cultivated in the shallow WTDs areas, where WTDs remain at somewhere between 0.45 and 0.75 m. If cotton is cultivated at WTDs between 1.50 and 2.75 m, it requires 63–88 % of the crop ET from surface irrigation in the Sultanpur soil series and 67–89 % in the Miani soil series. Cotton cultivated in deeper WTDs requires a higher fraction of the crop ET in the form of surface irrigation, as

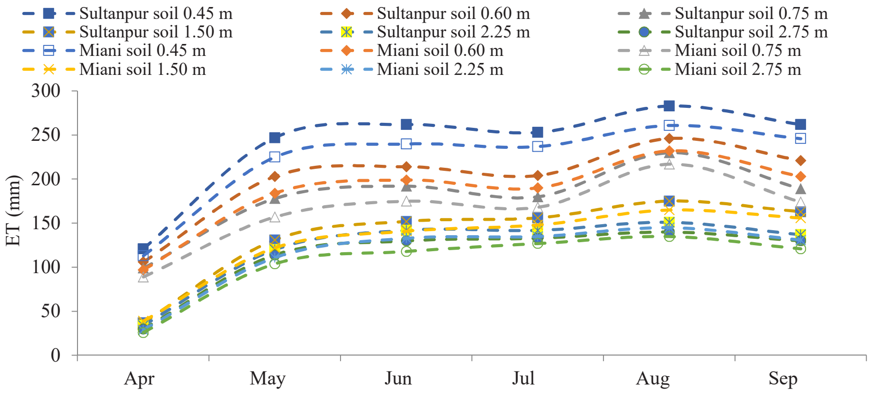

Fig. 7. Temporal variation in cotton ET at different WTDs and soil types.

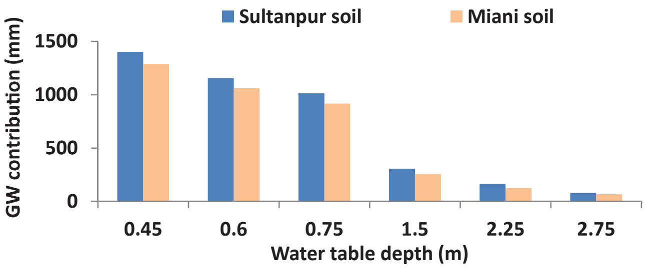

Fig. 8. The estimated lysimetric GW contribution to the cotton ET.

compared to those when it is cultivated in areas with a shallow WTD. These findings underline the fact that use of surface irrigation water and GW contribution should be taken into consideration for such a water-intensive crop (Kahlown et al., 2005; Gowing et al., 2009; Karimov et al., 2014; Gul et al., 2023a; Gul et al., 2023b).

No research has been carried out on cotton ET in Pakistan thus far. At a global scale, this holds especially true for cotton cultivated within lysimeters with 0.45–0.75 m WTDs. However, many researchers have estimated GW contribution to ET of other crops at WTDs between 0.50 and 3.00 m. In the Lower Indus Basin, Gul et al. (2018) found GW contribution of 94.8, 93.2 and 42.9 % to okra ET at 0.45, 0.60, and 0.75 m WTDs, respectively. Soybean uptakes 77, 71, 65, and 62 % of its water need from WTDs lying at 0.30, 0.50, 0.70 and 0.90 m, respectively (Fidantemiz et al., 2019).

Kahlown et al. (1998) revealed that GW contributed highly to the water need of wheat, if the WTDs are less than 1 m. In contrast, the role of GW contribution to meeting the crop ET was negligible when the WTD was around 2 or 3 m. Under the climatic conditions of central Punjab, Kahlown et al. (2005) identified that in a silty loam soil, wheat, sunflower and maize crops used 90, 80 and 40 % of the ET, respectively, through the GW contribution at 0.5 m WTD. For the sugarcane, barseem and sorghum crops, GW contribution to meeting their ET at 1.0 m WTD was 50, 30, and 10 %, respectively. In the sub-humid climatic conditions of China, wheat used 3 % of its total ET from a water table maintained at 3.0 m depth (Luo and Sophocleous, 2010). Liu and Luo (2011) used lysimeters for estimation of wheat ET. They pinpointed that GW contribution and precipitation meet 65 % of the wheat ET at WTDs between 0.40 and 1.50 m. However, water table managed at or less than 1.1 m fulfilled almost all of the wheat ET. Luo and Sophocleous (2010) showed wheat uptakes 75 % of its ET from water table maintained at 1.0 m, while it uptakes 3 % of ET when WTD is at 3 m. For wheat crop grown in lysimeters with varying magnitude of irrigation water, Huo et al. (2011) exhibited GW contribution of 29 % to the total ET at 1.50 m WTD.

Temporal variation in GW contribution to cotton ET at different WTDs is given in Fig. 9. At 0.45–0.75 m WTDs, the contribution of GW to ET increased starting from April (sowing time), followed by declination in July, an increase with its peak in August and again a declination in September (last fiber picking). It should be noted that the GW contribution reached to its maximum in August, when the WTDs were between 1.50 and 2.75 m. The increase in GW contribution to cotton ET from April and onward may be attributed to (i) small canopy and flowering stage during April, May and June, which could have resulted in high evaporation from the bare soil surface and maximum transpiration from the plant leaves and tissues, and (ii) to fully developed stage of the crop during the month of August (plants produced flowers, bolls and fibers simultaneously), thereby resulting in high evaporation and transpiration.

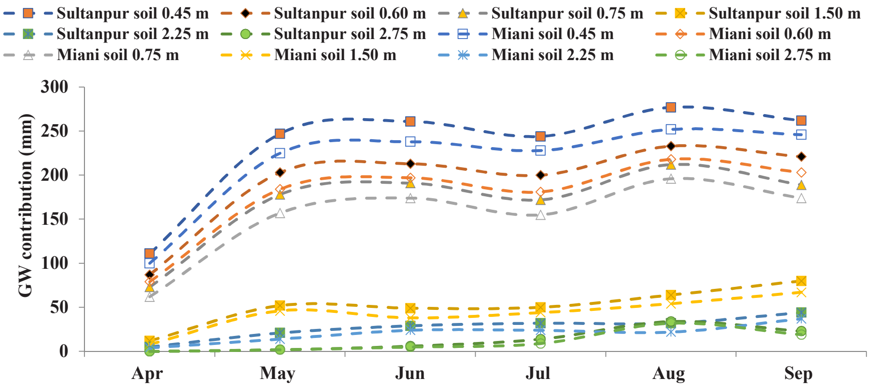

Fig. 9. Temporal variation in groundwater contribution to cotton evapotranspiration.

3.3. Yield and water use efficiency

Cotton yield was the lowest at 0.45 m WTD and increased with a decrease in water table (Fig. 10). The highest yield was observed at 1.50 m WTD, while the yield declined as the water table declined. When comparing cotton yield obtained at 1.50 m with that of obtained at 0.45–0.75 m WTDs, one can see it is 58–77 % lower in the Sultanpur soil series and 58–77 % lower in the Miani soil series. The highest yield produced at 1.50 m WTD may be attributed to the ET of the crop, which was satisfied from both sources, namely (i) moisture stored in the soil matrix in response to the irrigation and precipitation, and (ii) upward movement of water from capillary zone (GW contribution). The lowest yield resulted from 0.45 to 0.75 m WTDs may be associated with excessively submerged root-zone profile, thereby weakening the amount of aeration, and high soil salinity at 0.45–0.75 m WTDs also reduce the yield. Nosetto et al. (2009), Khan et al. (2008), Zhu et al. (2013) and Xu et al. (2013) corroborated our findings obtained in the present study.

Cotton WUE was identified to range from 0.07 to 0.62 kg/m^3 in the Sultanpur soil series and from 0.08 to 0.62 kg/m^3 in the Miani soil series at 0.45–2.75 m WTDs. Cotton WUE is the lowest at 0.45 m WTD and it is inversely correlated with decrease in water table. Our results are in line with that of Liu and Luo (2011). They revealed wheat WUE varied from 1.25 to 1.92 kg/m^3 at 0.40–1.50 m WTD. In China, Huo et al. (2011) exhibited the highest wheat WUE with 4.58 kg/m^3 occurred at 3.5 m WTD in comparison to 3.59 kg/m^3 obtained at 1.5 m WTD.

3.4. Agronomic parameters

At 1.50 m WTD, the sympodial branches are at their maximum rate as opposed to those of at shallower WTDs (i.e. 0.45–0.75 m) and deeper WTDs (i.e. 2.25–2.75 m). The tallest cotton plants and number of bolls/plant were witnessed at 1.50 m WTD and decreased either with changing the WTD from 0.45 to 0.75 m or with deepening the water table from 2.25 to 2.75 m (Table 1). This may be explained by the fact that the cotton plants were least exposed to water stress at 1.50 m WTD, where GW contribution to ET was dominant. This assessment is supported with conclusions drawn by Jayalalitha et al. (2015), Sahito et al. (2015) and Veesar et al. (2018). All of them reported huge variation in cotton sympodial branches in response to the water stress conditions. Moreover, at 0.45–0.75 m WTD, the sympodial branches were found to be the lowest due to a much shallower WTD, which lead to excessively submerged root-zone profile and thereby reducing the amount of aeration needed for the crop growth. She et al. (2022) found superior wheat agronomic parameters at 1.50 m WTD, while they reported the lowest wheat agronomic parameters as the WTD increased from 0.60 to 1.20 m.

3.5. Root zone salinity

The electrical conductivity (EC) of soil increased from 3.54 to 5.93 dS/m in the Sultanpur soil series and from 3.44 to 5.23 dS/m in the Miani soil type at 0.45–0.75 m WTDs, respectively (Table 2). The soil EC increased between 61 % and 78 % in the Sultanpur soil series and between 60 % and 69 % in the Miani soil type at 0.45–0.75 m WTDs, respectively. This increase in EC is mainly because of no irrigation was applied to the crop except for the soaking dose. The entire crop ET was fulfilled through the capillary water from WTD. When capillary rises under the presence of crop, a fraction of water is uptaken by plants and some evaporates, which leave behinds the salts. Under the same environmental condition, for growing Okra crop in mini lysimeters at 0.45–0.75 m WTDs, Gul et al. (2018) identified 14 % increase in the soil EC. The results of the current study are much higher than those reported by Gul et al. (2018). This is because they conducted study for just one cropping season (4 months), whereas current study was conducted for four cropping seasons (24 months). Hence, salinity buildup is subjected with the WTDs and the length of study period. Xu et al. (2013) concluded that if WTD is shallower than 1.0 m, then the salt concentration in root zone profile increases. Northey et al., (2006) concluded that soils underlain by shallow WTD pose a high risk to salinization due to the capillary rise of water from the water table bringing salts into the soil surface. However, salinization is highly dependent on the WTD and GW quality.

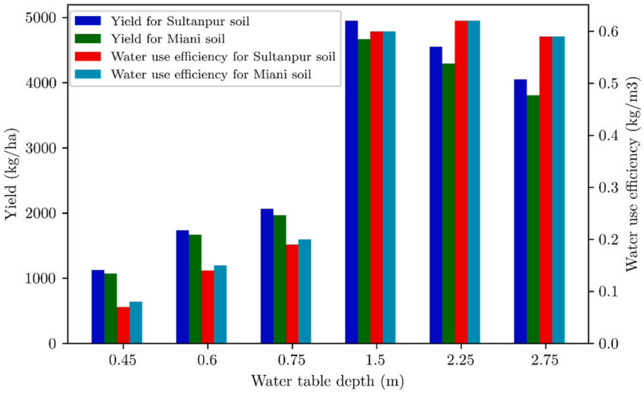

Fig. 10. Cotton yield and WUE at different WTDs and soil types.

Soil EC decreased at 1.50–2.75 m WTDs. This may be attributed to the periodic flushing of salts from the root zone with irrigation application and occurrence of rainfall (rainfall amounting to 16 mm during the cropping period of 2018 and highest rainfall of 213 mm in 2019 was recorded). Otherwise, salts may have buildup at time intervals of two irrigations. In a silty loamy soil, after 5 years of continuous experiments on wheat through both rain-fed and irrigated conditions at 1.50–3.0 m WTDs, Karimov et al. (2014) indicated 74–87 % increase in salt concentration in the soil under rain-fed conditions and salts flushed when irrigation water was applied in irrigated conditions.

The pH of soil decreased from 0.66 to 1.04 units in the Sultanpur soil series and likewise from 0.35 to1.33 units in the Miani soil type at 0.45–0.75 m WTDs, respectively (Table 3). However, after harvesting of second wheat crop in March 2020, pH values remained under the safe limit of 7.2–8.0 (USDA, 1969). The soil pH decreased between 8 % and 17 % at 0.45–0.75 m WTDs and between 4 % and 10 % at 1.50–2.75 m WTDs under both soil types, respectively. The decrease in pH is mainly associated with the application of synthetic urea fertilizer. Our findings also match to investigations undertaken by Benbi and Brar (2009), Czarnecki and During (2015), Liang et al. (2012) and Lu et al. (2004). These investigators reported that the use of synthetic fertilizers decrease the soil pH value because of nitrification and acidification processes and also because of the release of H$^+$ by plant roots. Under the same environmental condition, for growing Okra crop in the mini lysimeters at 0.45–0.75 m WTDs, Gul et al. (2018) showed 3 % decrease in the soil pH. The results of the current study are much higher than those reported by Gul et al. (2018). Similar to the finding revealed for the soil EC, this is because they conducted study for just one cropping season (4 months), whereas current study was conducted for four cropping seasons (24 months). Soil pH decreased maximum at 0.45–0.75 m WTDs as compared to 1.50–2.75 m WTDs. Since half of the Urea fertilizer was applied as basal dose with soaking dose before sowing of crop in each season, thereafter, no irrigation was required, and crop meet all its ET from water table through capillary rise at 0.45–0.75 m WTDs. Hence, urea fertilizer will remain in the soil profile and does not leach out. In this case, urea fertilizer available in the soil column will get the utmost opportunity to dissolve through the capillary water coming from water table; thereby will reduce maximum soil pH. Whereas irrigation application was made in 1.50 m to 2.75 m water table, in this case fertilizer will be dissolved; some amount will remain in soil profile and other leach out. Therefore, in the presence of shallow WTDs, decrease in pH is mainly associated with synthetic urea fertilizer. It has been reported that the use of synthetic fertilizers decreases the soil pH value because of nitrification and acidification processes (Czarnecki and During, 2015;

Table 1
Cotton agronomic data (Average of 2018 and 2019).

Parameters	Sultanpur soil						Miani soil						SE*	LSD*
WTD (m)	0.45	0.60	0.75	1.50	2.25	2.75	0.45	0.60	0.75	1.50	2.25	2.75		
Sympodial braches (Nos.)	13	15	18	33	31	26	11	13	16	28	24	23	0.29	0.41
Plant height (m)	0.60	0.72	0.8	1.41	1.32	1.19	0.55	0.66	0.77	1.24	1.18	1.10	0.04	0.06
Biomass (kg/plant)	0.12	0.14	0.16	0.29	0.25	0.23	0.10	0.12	0.13	0.24	0.23	0.19	0.01	0.01
Bolls/plant (Nos.)	18	21	25	44	38	35b	17	19	22	35	33	32	1.06	1.50

* SE and LSD stand for Standard Error and Least Significant Difference, respectively.

Table 2
The soil EC (dS/m) before sowing of cotton (April 2018) and after harvesting of wheat (March 2020).

WTDs (m)	Sultanpur soil			Miani soil		
	Before	After	Diff	Before	After	Diff
0.45	1.66	7.59	5.93	2.33	7.56	5.23
0.60	2.00	6.67	4.67	2.00	5.52	3.52
0.75	2.31	5.85	3.54	2.31	5.75	3.44
1.50	3.74	3.37	- 0.37	3.73	3.01	- 0.72
2.25	3.49	3.00	- 0.49	3.41	2.64	- 0.77
2.75	3.07	2.36	- 0.71	3.66	2.62	- 1.04
SE	0.0299					
LSD	0.0424					

Table 3
The soil pH before sowing of cotton (April 2018) and after harvesting of wheat (March 2020).

WTDs (m)	Sultanpur soil			Miani soil		
	Before	After	Diff	Before	After	Diff
0.45	8.08	7.42	- 0.66	8.02	7.00	- 1.02
0.60	7.98	7.15	- 0.83	7.80	6.65	- 1.15
0.75	8.17	7.13	- 1.04	7.85	6.52	- 1.33
1.50	8.15	7.47	- 0.68	7.98	7.63	- 0.35
2.25	8.00	7.3	- 0.70	7.95	7.45	- 0.50
2.75	8.17	7.35	- 0.82	8.17	7.55	- 0.62
SE	0.005774					
LSD	0.008165					

Liang et al., 2012; Benbi and Brar, 2009; Lu et al., 2004).

The Soil SAR increased from 0.67 to 2.98 units in the Sultanpur soil type and similarly from 0.43 to 1.63 units in the Miani soil type at 0.45–0.75 m WTDs (Table 4). The soil SAR increased from 10 % to 38 % at the WTDs varying from 0.45–0.75 m under both soil types. The increase in SAR implies that the highest content of exchangeable Na^+ has accumulated in the soil matrix. However, SAR remained in a safe limit of <13 (Horneck et al., 2007). In the same vein, SAR decreased 13–25 % at WTDs varying from 1.50 to 2.75 m under both soil types. The decrease in the soil SAR values indicates that concentration of exchangeable Na^+ in the soil is reduced. A decline in SAR might be due to (i) irrigation applications and strong storm events occurred during 2019 and (ii) plant salt uptake (Gul et al., 2021). Similar findings were reported by Khan et al. (2008). They concluded that the soil SAR increases by 85 % when the water table is maintained at 1.16 m.

The Soil ESP increased from 0.61 to 3.75 units in the Sultanpur soil type and from 0.39 to 1.86 units in the Miani soil type at 0.45–0.75 m WTDs (Table 5). In other words, the soil ESP increased 5–40 % at 0.45–0.75 m WTDs under both soil types. In contrast, it decreased from 14 % to 28 % at 1.50–2.75 m WTD. An increase in ESP shows that the highest content of exchangeable Na^+ has accumulated. It is also concluded by Verma et al. (2012) that the soil ESP increases in a shallower WTD and vice versa. The same reasoning for decline in SAR can be extended to the reduction of ESP, which are (i) irrigation applications and strong storm events occurred during 2019, and (ii) plant salt uptake (Gul et al., 2021). ESP values remained under the permissible range of <15 (Horneck et al., 2007).

4. Conclusions

Determining the ET of cotton, known for its high-water demand, is vital for efficient irrigation planning and water management, particularly in regions like Sindh province, Pakistan, where shallow WTDs are prevalent. Despite cotton's significance as a major cash crop in Sindh, previous studies on its ET were conducted decades ago and may no longer be reliable due to the ongoing impacts of climate change and the introduction of new crop varieties. To address this, we conducted a two-year lysimetric research study (2018 and 2019), quantifying cotton ET across two cropping seasons and at various WTDs (0.45, 0.60, 0.75, 1.50, 2.25, and 2.75 m) in two soil series.

The study revealed that cotton ET varied across depths, ranging from 1332 to 1437 mm, 1114–1202, 988–1075, 781–821, 690–733, and 637–683 mm. Water tables between 0.45 and 0.75 m fulfilled 94–96 % of ET through GW contribution in Sultanpur soil and 93–97 % in Miani soil. At 1.50–2.75 m WTDs, GW contribution reduces irrigation requirements (excluding rainfall and leaching) to 63–88 % in Sultanpur soil and 67–89 % in Miani soil. The highest yield was observed at 1.50 m WTD and highest WUE at a 2.25 m WTD. However, soil salinity increased by 60–80 %, resulting in a 40–60 % lower cotton yield at 0.45–0.75 m WTDs. Therefore, periodic flushing of salts is necessary to effectively utilize shallow WTDs.

It is essential to take into account the GW contribution to ET during the allocation of water for irrigation channels and the development of

Table 4
The sodium adsorption ratio (SAR) before sowing of cotton (April 2018) and after harvesting of wheat (March 2020).

WTDs (m)	Sultanpur soil			Miani soil		
	Before	After	Diff	Before	After	Diff
0.45	4.82	7.80	2.98	6.23	7.86	1.63
0.60	5.46	6.86	1.40	5.59	6.67	1.08
0.75	6.20	6.87	0.67	5.77	6.20	0.43
1.50	6.78	5.91	- 0.87	6.99	6.04	- 0.95
2.25	6.34	5.16	- 1.18	6.61	5.17	- 1.44
2.75	6.85	5.22	- 1.63	7.31	5.47	- 1.84
SE	0.0209					
LSD	0.0295					

Table 5
The exchangeable sodium percentage (ESP) data before sowing of cotton (April 2018) and after harvesting of wheat (March 2020).

WTDs (m)	Sultanpur soil			Miani soil		
	Before	After	Diff	Before	After	Diff
0.45	5.52	9.27	3.75	7.27	9.13	1.86
0.60	6.36	7.92	1.56	6.52	7.76	1.24
0.75	7.30	7.91	0.61	6.76	7.15	0.39
1.50	7.85	6.74	- 1.11	8.11	6.91	- 1.20
2.25	7.27	5.78	- 1.49	7.64	5.77	- 1.87
2.75	7.94	5.85	- 2.09	8.5	6.16	- 2.34
SE	0.0209					
LSD	0.0295					

irrigation schedules. This practice can result in conserving water, averting waterlogging and salinity in the land, effectively managing the water table, and diminishing the necessity for drainage channels and associated labor efforts.

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CRediT authorship contribution statement

Munir Ahmed Mangrio: Supervision, Software, Formal analysis, Data curation. **Irfan Ahmed Shaikh:** Writing – review & editing, Writing – original draft, Supervision, Data curation. **Abdul Ghafoor Siyal:** Writing – review & editing, Writing – original draft, Supervision, Formal analysis, Data curation, Conceptualization. **Majid Taie Semiromi:** Writing – review & editing, Data curation. **Nazar Gul:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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