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CONTROLLED SUBSURFACE DRAINAGE AS A STRATEGY FOR IMPROVED WATER MANAGEMENT IN IRRIGATED AGRICULTURE OF UZBEKISTAN[†]

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ABSTRACT

An existing conventional drainage (CVD) was modified to control the flow from the drainage lateral and to control the groundwater table depth on a portion of irrigated winter wheat during the 2014–2015 cropping season in the Fergana Valley, Uzbekistan. Drainage outflow at one of two drainages was controlled (CTD), while the other was free (CVD). The cumulative drainage water volume from the CVD treatment was 22% greater than the CTD treatment. The flow-weighted mean salt concentration of the drainage water was on 7% lower in the CTD treatment (2.08 mS cm^{-1}) compared to the CVD treatment (2.24 mS cm^{-1}). The ratio of soil water content in the 1 m soil profile between inspection sumps A and B (1) versus B and the open collector (2) was 1.2, suggesting that the upper part of the field contained 20% more soil moisture. Conversely, the ratio of the groundwater table depth between (1) and (2) was 0.78, indicating that the groundwater table of the upper portion of the field was 47 cm (22%) shallower than the lower part. Thus, CTD increased the moisture storage of the soil layer in the upper part of the field. Managing the groundwater table resulted in less water stress between irrigation events and increased grain yields. © 2018 John Wiley & Sons, Ltd.

KEY WORDS: controlled drainage; groundwater table; drainage outflow; wheat yield

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RÉSUMÉ

Un drainage conventionnel existant a été modifié pour contrôler le débit du drainage latéral et pour contrôler la profondeur de la nappe phréatique sur une partie du blé d'hiver irrigué pendant la saison de récolte 2014–2015 dans la vallée de Fergana, en Ouzbékistan. Le débit du drainage contrôlé (CTD) a été mesuré et comparé à celui du drainage conventionel dont l'écoulement était libre (CVD). La lame d'eau drainée provenant du traitement CVD était de 22% supérieur au traitement CTD. La concentration saline moyenne pondérée en fonction du débit de drainage était inférieure de 7% au traitement CTD (2.08 mS cm^{-1}) par rapport au traitement CVD (2.24 mS cm^{-1}). Le rapport de la teneur en eau du sol dans le profil de sol de 1 m entre les puits d'inspection A et B (1) vs B et le collecteur ouvert (2) était de 1.2, suggérant que la teneur en eau du sol de la partie supérieure du champ contenait était 20% plus élevée. Inversement, le rapport de la profondeur de la nappe phréatique entre (1) et (2) était de 0.78, indiquant que la nappe phréatique de la partie supérieure du champ était de 47 cm (22%) moins profonde que la partie inférieure. Ainsi, CTD a augmenté le stockage d'humidité de la couche de sol à la partie supérieure du champ. La gestion de la nappe phréatique a entraîné moins de stress hydrique entre les périodes d'irrigation et l'augmentation des rendements céréaliers. © 2018 John Wiley & Sons, Ltd.

MOTS CLÉS: drainage contrôlé: nappe phréatique; écoulement de drainage; rendement du blé

INTRODUCTION

The rapid expansion of irrigated lands during 1960–1980 in Uzbekistan has been followed by installation of drainage systems in response to waterlogging and salinity problems. Currently, the artificially drained area in Uzbekistan covers about 2.9 Mha (million hectares), of which 19% (about 13% of the country's irrigated land) constitutes subsurface drainage systems (Dukhovny *et al.*, 2007). Depending on hydrological and economic conditions, the depth of the subsurface drainage installation is usually 0.3–1.0 m deeper than the active groundwater table (GWT), while spacing between two laterals is not less than 50 m (Dukhovny *et al.*,

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2005a, 2005b, 2007). A peculiarity of drainage systems in arid areas is that installation depth and lateral spacing are nearly twice as deep and 4–5 times greater than those in humid areas, respectively (Ayars, 1996). However, the principal differences of subsurface drainage system design in arid areas compared to those in humid areas are grounded on the peculiarity of natural-climatic conditions (high evaporation intensity, moisture deficit, soil salinity, etc.), stipulating deeper installation (2.5–3.5 m against 0.8–1.2 m), less intensity, considerably higher designed discharge and therefore a deeper GWT and higher surface water application for agricultural crops. However, there is no need to drain soil much deeper than the root zone.

Another peculiarity of these drainage systems is their design, which discharges water continuously without regard to environmental consequences. Conventional agricultural land drainage systems are usually over-designed to cope with worst-case situations in terms of crop rooting depths and drainage requirements, as well as the expected loss of performance as systems age. For many crops and for much of the time this results in more water being removed from the soil profile and passed to drains than is necessary to control waterlogging or to mitigate salt build-up in the soil profile. Analysis of the approximate water–salt balance at district level across provinces of Uzbekistan demonstrated that the majority of drainage systems were over-draining, as they were removing 2.3 times more salt than was applied by irrigation water (Figure 1). In general, farmers frequently over-irrigate to compensate for rapid removal of water by drainage systems.

Negative environmental impacts caused by mismanagement, deterioration and ageing of collector drainage networks are accompanied by the lack of return water effluent management into the main rivers, lakes and lowlands, releasing salts and pollutants from different water management sectors. Coupled with that, the increase of water mineralization in the Syrdarya and Amudarya rivers was observed in time and along the course since 1950–1970 (Kenjabaev, 2014). Moreover, existing irrigation system efficiency is low, being 0.48–0.73, thus only 30–35% of water drawn from the source is used for irrigation of agricultural crops (Ikramov, 2007). Partial water losses return to the main stream as a return flow from collector drainage systems. Hence, mean multi-year stocks of collector drainage water (CDW) in Uzbekistan total 21±2 km^3. About 95% out of the total return CDW comes from irrigated lands and is almost 43±6% of total agricultural water withdrawal (CAWATERinfo, 2016).

One of the ways to solve the problem of further development of water management in the agrarian sector is elaboration of large-scale measures to reduce collector drainage runoff by reuse where it is generated (Berdjansky and Zaks, 1996). Nowadays about 13% of total return water is reused for irrigation purposes (Dukhovny *et al.,* 2007), mainly in upper and middle course provinces of Uzbekistan. Although conventional drainage decreases soil salinity under leaching/irrigation mode, improves soil aeration and thereby machine trafficability, and increases crop yields (Dukhovny *et al.,* 1979, Madramootoo *et al.,* 2007), it can also lead to soil water stress during dry periods. As Ayars (1996) stated,

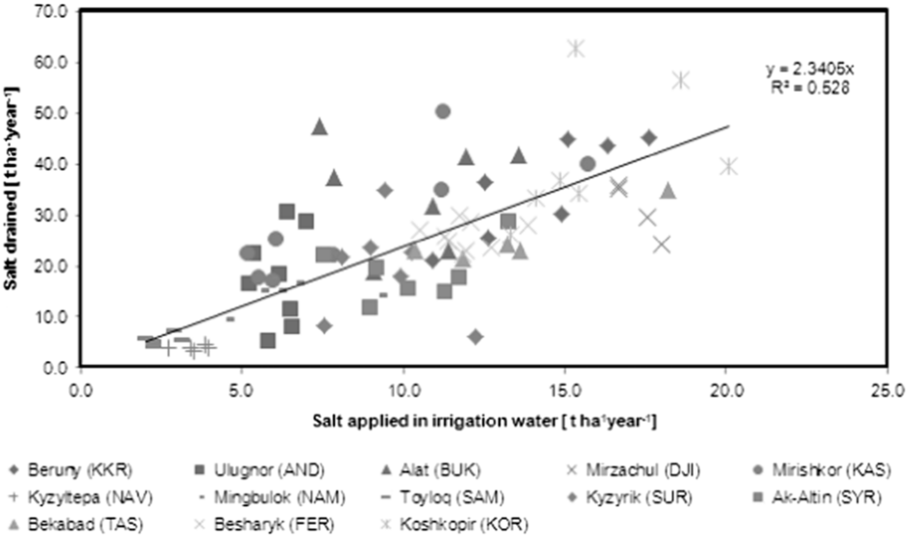

Figure 1. Salt loads in irrigation water and drainage water for various irrigation districts in Uzbekistan (based on data for 1995–2003 from the Ministry of Agriculture and Water Resources, Republic of Uzbekistan). Letters in parentheses: KKR: Karakalpakistan Republic, AND: Andijan, BUK: Bukhara, DJI: Djizakh, KAS: Kashkadarya, NAV: Navoi, NAM: Namangan, SAM: Samarkand, SUR: Surkhandarya, SYR: Syrdarya, TAS: TAshkent, FER: Fergana, KOR: Khorezm provinces of the corresponding districts.

'in arid areas, subsurface drainage design is based on the concept of "dynamic equilibrium", which assumes that the range of the cyclic annual water table fluctuation is constant'. Therefore, the mid-point GWT height reaches the maximum height above the drains at the same time each year, generally by the end of the growing season. Moreover, the laterals in a subsurface drainage system design in arid areas are typically laid parallel to the surface grade of the field being drained. Hence retrofitting an older system to include control structures may not be practical because the slope of the field and drain laterals may require many control structures in the field (Ayars and Schoneman, 2006). The challenge for the most effective GWT management system is to find a drainage system where the laterals have been installed perpendicular to the surface grade or to develop a new system design and installation which enables GWT control over a large part of the field with a minimum number of control structures.

Coupled with that, there needs to be a new approach to subsurface drainage that applies management to these drainage systems in order to reduce their downstream environmental impacts whilst maintaining agricultural production. Controlled drainage may be an option with an existing drainage system as it contributes a reduced drainage flow and lower irrigation requirements. Hence it can help farmers to better manage soil moisture by removing excess water in wet periods as well as to retain moisture in the field during dry periods through regulation of the drain outlets (Singh *et al.,* 2014). In addition, in a controlled drainage system the GWT is maintained at a shallower depth by a control structure which reduces percolation below the root zone by reducing hydraulic gradients and increases potential capillary upflow as evapotranspiration depletes soil water in the root zone. Moreover, the flow lines, in controlled drainage areas, are shallower than in uncontrolled systems and are concentrated closer to the soil surface. This will result in decreased drain water salinity in soil profiles, with zones of lower soil salinity at the soil surface compared to uncontrolled systems. Hence, the reduced drain flows and lower salinity result in much reduced salt loads, while their downstream environmental impacts are minimized. However, it seems that more local research will be required to reach new standards and design criteria leading to optimizing technical, economic and environmental issues. After carrying out research, a reduction in drainage environmental problems would be expected when alternative methods are practised. Therefore, the aim of this study was to learn how the management of the GWT by controlled subsurface drainage will provide the opportunity to increase *in situ* crop water use, which should result in improved irrigation efficiency and reduced drainage outflow.

MATERIALS AND METHODS

Site description

The experimental site, the so-called 'Azizbek' site (40º28′ N, 71º32′ E) is situated in the Oktepa Kyrgizobod Ziloli water users' association in the command area of the Naryn-Fergana administrative irrigation system of Fergana province, Uzbekistan. Two fields at the experimental farm of SANIIRI's branch in Fergana were selected as subjects of research. The fields lie within the irrigation zone of the Big Fergana Canal in the flat smooth proluvial plain that constitutes the peripheral part of the alluvial cone of the small Margilansay, Shahimardansay and Isfaramsay transboundary rivers (Stulina *et al.,* 2005). Slopes are northward and relatively plain, being 0.002–0.003 (Stulina *et al.,* 2005, Dukhovny *et al.,* 2005a). Water for irrigation is distributed to the fields through a 4-km-long concrete-flume canal 'Pakhtakor-4' delivering water from the Big Fergana Canal. Hence the fields suffer from frequent water shortages due to improper water management within the system as well as their location at the course of the canal. Field agronomic monitoring as well as research was conducted on two fields (contours: 13 and 14, 20.2 ha and 15 and 16, 16.3 ha), with a total area of 36.5 ha (Figure 2).

The study site is in the Central Climatic zone (C II) (Food and Agriculture Organization of the United Nations (FAO), 2003). The general climatic characteristics of the region according to Köppen-Geiger climate classification vary with typical continental, cold, arid, desert and steppe climates (BWk and BSk) (Kottek *et al.,* 2006). The climatic conditions of the study region are characterized by data from the Fergana meteorological station. There is a temperature regime with mean annual air temperature during the period being +15.3°C. Mean air temperature during the vegetation period (from 1 April 2015 to 30 September 2015) and non-vegetation period (from 1 October 2014 to 31 March 2015) was +23.7°C and +5.9°C, respectively. Mean wind velocity during 2001–2015 was 1.2 m s^{-1}, with the daily value fluctuating from 0 to 8.0 m s^{-1}. Mean relative humidity during 2001–2013 was 64%. The average daily relative humidity during the non-vegetation period (October 2014–March 2015) and vegetation period (April–September 2015) was 78 and 55%, respectively. Mean daily sunshine duration during 2001–2015 ranged from 3.3 to 8.0 h, with the maximum being 13.8 h. Precipitation data show that there was relatively similar rainfall during the growing season in 2014 (68 mm) and 2015 (59 mm) compared with the 13-year average annual precipitation (67 mm). However, this amount is not evenly distributed throughout the year and about 64% of rainfall falls during the non-growing period (October–March). Reference evapotranspiration (ET_0) during 2001–2015 fluctuated from 0.3 to 10.3 mm day^{-1} with a mean value for the period 3.2 mm day^{-1}. Total calculated ET_0 for the vegetation period

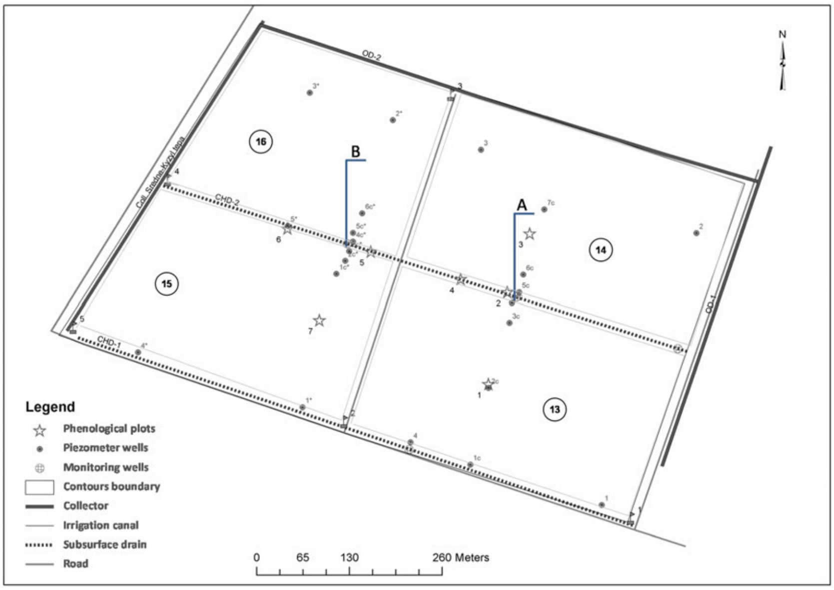

Figure 2. General overview of the experimental site. [Colour figure can be viewed at wileyonlinelibrary.com]

in 2014 and 2015 as well as the non-vegetation period in 2014–2015 was 1100 and 850 mm and 215 mm, respectively.

The lithological structure is presented by melkozems and a sandy stratum with less depth. According to the Russian classification, soils are calcic sierozem and loams are less permeable (percolation rate 0.2–2.0 m day^{-1}). They are formed on alluvial-proluvial deposits of talus train. According to the FAO classification, soils are calcaric gleysols (Gc) (FAO, 2003) in which there is substantial secondary accumulation of lime, and it has a gleyic colour pattern. According to the World Reference Base for soil resources (International Union of Soil Science (IUSS) Working Group World Reference Base (WRB), 2006), the common name for many gleysols is gley and meadow soils.

In terms of hydrology, the study site is located within the area of a shallow GWT and groundwater discharge zone influenced by both groundwater and artesian water. Artesian water is exposed at a depth of 120–200 m and is related to sandy-gravel sediments of the Golodnostepsky and Tashkent system. The GWT fluctuation is 1.0–2.6 m (even shallower during irrigation events) and is located within the sandy loam and loam layers, with groundwater salinity ranging from 2.9 to 4.6 g l^{-1}. Groundwater salinity is higher at deeper levels. Chemical composition of groundwater is sulphate-chloride and sulphate. The GWT gradient is north-westward with a gradient of 0.002–0.0025, which indicates weak drainability.

Agronomical practices and phenological observation

Winter wheat (*Triticum aestivum* L.) variety 'Tanya' was sown by broadcasting with a seeding rate of 240–260 kg ha^{-1}, under not yet harvested cotton on 7–8 October 2014 in field contours C-13 and 14, and on 15 October 2014 in field contours C-15 and 16. One or two times cultivation was conducted in cotton fields before and after wheat was sown in order to incorporate seeds into the soil. Phenological observations of wheat (plant height and root depth at bi-weekly intervals and plant density at maturity and yield at harvest) were performed on 7 plots with plot size of 1 m^2 following the approach proposed by Dospekhov (1985). Plant density ranged from 228 (plot 5) to 507 (plot 1) plants m^{-2}. Fertilization was carried out by tractor broadcast (with aggregate NRU-0.5). The total amount of nitrogen (N) comprised 250-275 kg N ha^{-1} (in nutrient form) during the growing season of wheat. N was applied in three splits during the growing period. Six irrigations with a gross amount of 530 and 550 mm were carried out during the wheat growth period on field contours C-13 and 14 and C-15 and 16, respectively (Table I). The length of the total growing period (life cycle) of wheat ranged from 246 (C-15 and 16) to 250 (C-13 and 14) days. In addition, soil moisture, soil salinity and GWT were measured routinely using state-of-the-art devices on nearby phonological plots (Figure 2). Installed state-of-the-art devices are described in the following sections.

Design characteristics of the subsurface drainage system

The site is bordered by open drains (OD-1 and OD-2) on the south and south-east roads in the west and the Srednekyzyltepa collector in the north-west (Figure 2). Two closed horizontal drains (CHDs) were made out of asbestos-cement tubes perforated in the bottom with 11

Table I. Date and irrigation amount for winter wheat in fields C-13 and 14 and C-15 and 16

Irrigation No.	Start and end date of irrigation		Gross irrigation (mm)	
	C-13 and 14	C-15 and 16	C-13 and 14	C-15 and 16
1	13–14 October 2014	16–24 October 2014	125	75
2	20–26 January 2015	12–20 January 2015	119	129
3	18–23 March 2015	12–20 March 2015	109	83
4	23–28 April 2015	25–30 April 2015	61	87
5	10–19 May 2015	13–20 May 2015	92	133
6	29 May–6 June 2015	29 May–6 June 2015	27	40
Total			533	547

openings (Ø = 0.8 cm) at 1 m length and surrounded by sand-gravel as a filter (Shamsutdinov, 1966). The specific length of subsurface drainage is 25 m ha^{-1}. The drains have been operating for the last 55 years. Both drains discharge their water into the Srednekyzyltepa collector, which has a depth of 3.5–3.7 m, bottom width of 1–1.5 m and bank slope of 1:1.25-1:1.5. The design parameters of the closed horizontal drains are given in Table II. Two and three observation wells (inspection sump) made from reinforced concrete with depth and diameter of 100 × 100 cm were installed with four sections in CHD-1 and CHD-2, respectively (Figure 3A). However, one of the two observation wells was operating in CHD-1 before the start of the design. Hence, the second well was cleaned as well in order to create a free water flow into the collector.

Experimental design

Installation of control structureBased on existing groundwater control construction techniques (Nyvall, 1998, Singh, 2013, Wesström *et al.,* 2014), the polyvinyl chloride (PVC) risers on the drain laterals to the control drainpipe outlet used by Hornbuckle *et al*. (2005) seemed to be more practical and cost-effective. Hence, a similar PVC riser was developed manually and entered into a drainpipe outlet in the monitoring well (inspection sump) in order to grab the free water flow. Sump sections are hermitically sealed with cement and further covered by bitumen in order to prevent raised water outflow from the sump. The third and fourth sections of the inspection sump were marked with red and blue colours with 10-cm scale increments in order for easy

Table II. Design parameters of the subsurface horizontal drainage system in the experimental site

Sub-surface drain No.	Service area (ha)	Depth (m)	Slope	Spacing (m)	Length (m)	Inner diameter of pipe (mm)	Pipe type	Designed modulus ($l\ s^{-1}\ ha^{-1}$)
CHD-1	40	3.2	0.0025	250	1670	147	Asbestos-cement	0.17
CHD-2	20		0.002		750			

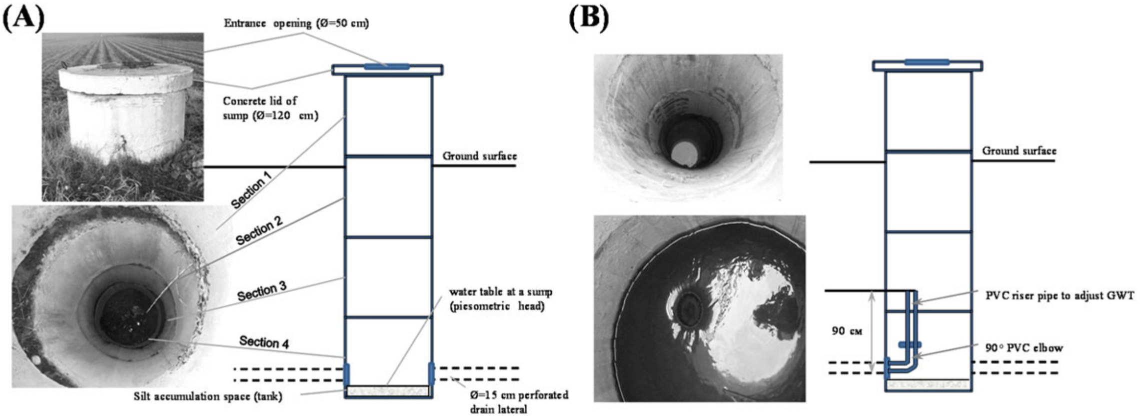

Figure 3. Cross-section of inspection sump (A) and raised GWT after installation of the pipe riser on lateral drain (B). [Colour figure can be viewed at wileyonlinelibrary.com]

visual monitoring of the water level rise between the drainage pipe bottom and riser opening (Figure 3B).

In this experiment, CHD-1 was left as a free outlet drain due to difficulties in cleaning the drainpipe. Therefore it operated in submerged mode during the observations and was considered as similar to controlled drainage. For controlled drainage, CHD-2 was considered. The outlet was closed at two sections of the CHD-2 pipeline (e.g. at the inspection sump A and B, Figure 2). Water discharged through outlet A when the GWT rose above the desired 90 cm level, and was then captured at outlet B. The raised GWT above the desired level at outlet B thereafter flowed freely into the open Srednekyzyltep collector.

Monitoring of drainage water flow volumes and salinity was undertaken at both drainpipe outlets. The drainage volume was measured at 5–10-day intervals (daily during irrigation events) with an already installed Chippoletti weir with a bottom width of 50 cm. Drainage water salinity was measured *in situ* using an ES-2 sensor (Decagon Devices, Inc.) and ProCheck handheld reader (ICT International).

Installation of groundwater table monitoring piezometersIn total, 22 piezometer wells were installed (see Figure 2 for location), using a hand-operated auger drill in the experimental site in order to study the groundwater regime between subsurface drains. Wells are made out of PVC pipe (Ø 40 mm), with a length of ~3.33 m, perforated (Ø 3–4 mm) from the bottom depth of 1.2 m and covered by thin synthetic material (Ø 0.3 mm, approximately) as a filter to prevent silting. A man-made flap (*xlopushka*) and 3.5 m ruler tape were used to measure GWT. Measurements were performed at a frequency of 5–6 days from 26 October 2014 to 15 June 2015.

Installation of state-of-the-art devices. The following devices were installed near to the phenological plots. Four 5TE sensors (Decagon Devices, Inc.) with increments of depth 0–30, 30–60, 60–90 and 90-120 cm and one CTD-10 sensor (Decagon Devices, Inc.) were installed near the piezometers on phenological plots 1, 2, 3 and 6 in order to measure the soil moisture content and GWT, respectively. In addition, five 5TE sensors with increments of depth 0–30, 30–60, 60–90, 90–120 and 120–150 cm were installed on phenological plot 5. All these sensors were wired into EM50G data loggers on 3–4 March 2015 and removed on 14–15 June 2015 before the harvest of winter wheat. Measurements were taken on an hourly basis.

RESULTS AND DISCUSSION

Crop growth

From sowing date to emergence (9–10 days), mean daily air temperature ranged from 12.5 to 15.6 °C. Prolonged periods with daily air temperature below 5°C (26 Nov. 2014–22 Feb. 2015) caused dormancy in the wheat. Optimum growth started when the mean daily temperature was between 15 and 23°C. Grain filling started on 20–25 May 2015 when the mean daily temperature ranged between 21 and 25°C.

Figure 4 shows the development of height and rooting depth at seven phenological plots during the main growing period of wheat. Based on this figure, it can be noted that plant height on 30 May 2015 (maturity stage) is relatively taller in plots 2, 4 and 5 (along CHD-2), ranging from 79.5 to 104 cm, whereas plant root depth is shallower, for example, 59–64 cm on these plots compared to that on plots 1, 3 and 6 (74–77 and 59–71 cm). From these values, it is evident that root depth in the plots beside from the CHD-2 line penetrated deeper due to an increase in GWT depth. In contrast, the lower root depth of plots 2, 4 and 5 mainly resulted from the GWT restricting downward penetration of the root system. Brisson *et al.* (2002) reported that root growth slowed down and stopped when the oxygen concentration of the soil was below a critical value due to the soil moisture content being saturated. This indicates that a shallower GWT decreases plant root water uptake and thus reduces root development. These parameters in plot 7 (in-between CHD-1 and CHD-2) are almost the same as those observed in plot 6.

Drainage water level

The water level of the drainage monitoring wells in sections A and B is presented in Figure 5. The water level of the drainpipe outlets was elevated for the first time on 20 March 2015 when the third vegetative irrigation started in C-13 and 14 (during that time irrigation was stopped in fields C-14 and 15). Although irrigation started on 18 March in C-13 and 14, the initial groundwater level was raised to 45 and 70 cm above the drain outlet levels at the monitoring wells (inspection sumps) A and B, respectively. Because the third irrigation on field contour C-15 and 16 finished on 20 March, the maximum water level at well B was smaller (111 cm) compared to well A (200 cm). Starting in the third decade of April, when the fourth vegetative irrigation was initiated, the groundwater levels rose from 58 and 68 cm to 158 and 148 cm above the drain in wells A and B, respectively. It should be noted that the control structure was not removed during the vegetation period of wheat. This is due to fact that operating open drains (OD-2) and the collector (Srednekyzyltepa), as well as the existence of sand and sand-gravel layers at the depth of 1.5–1.75 m, apart 30–75 m from the subsurface drain CHD-2 line in the C-13 and 14, had a greatest impact on maintaining the GWT. This enabled the GWT to be maintained between 90 and 251 cm above the drainpipe level throughout the fifth and sixth irrigations.

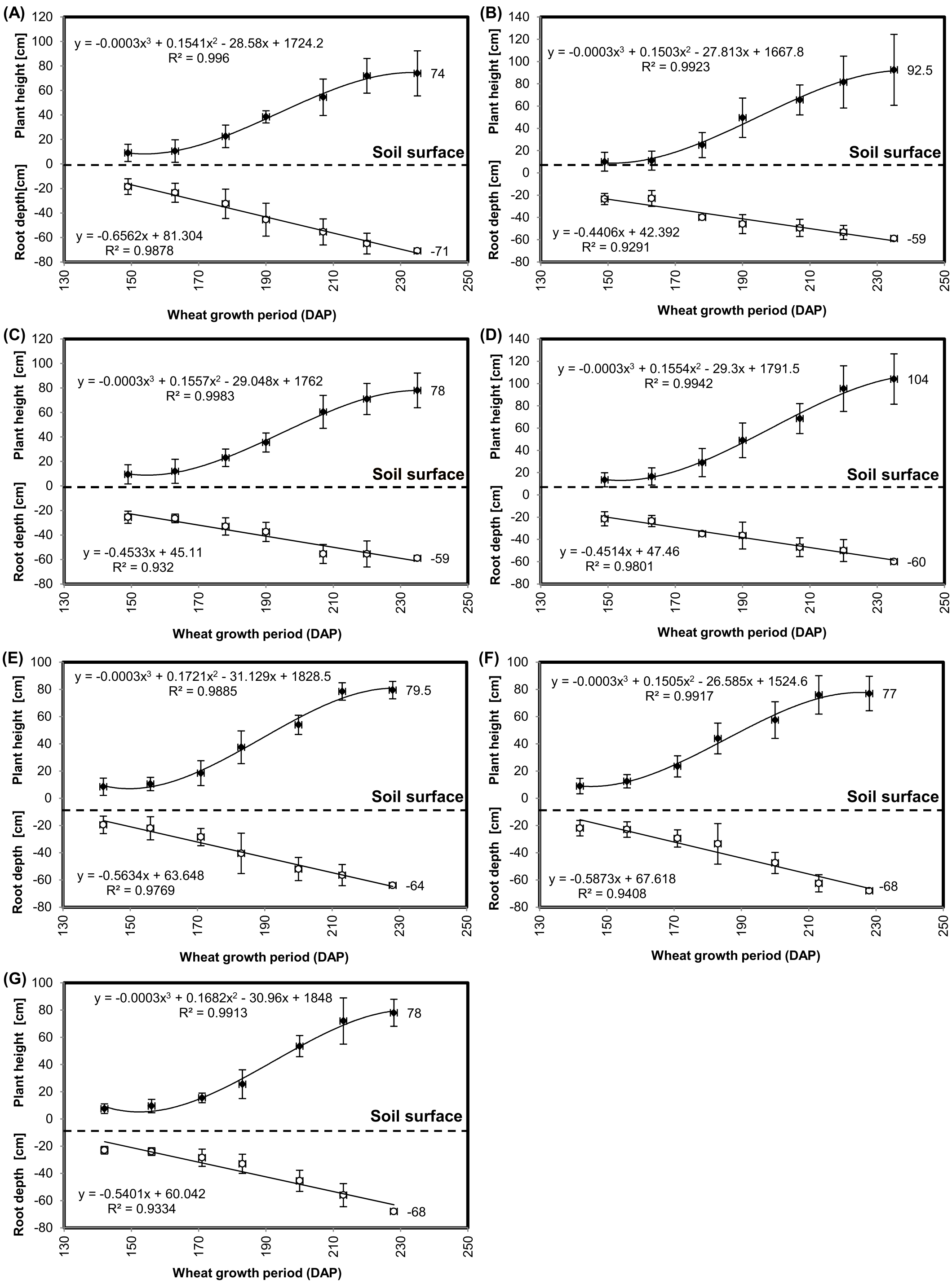

Figure 4. Dynamics of height and rooting depth of winter wheat during the growth period (day after planting, DAP) in plot 1 (A), plot 2 (B), plot 3 (C), plot 4 (D), plot 5 (E), plot 6 (F) and plot 7 (G) (for plot location refer to Figure 2).

Soil moisture

Soil moisture measured by the 5TE sensor from 4 March to 16 April on phenological plots 1 (A), 2 (B) and 3 (C) at field contours C-13 and 14 is given in Figure 6. Hence, the irrigation in each application was rotated within a field (e.g. 60–100 furrows simultaneously irrigated within a day, then water was applied for the next 60–100 furrows the following day and so on); the rise of the soil moisture content (SMC) is concomitant to that point where irrigation water reaches

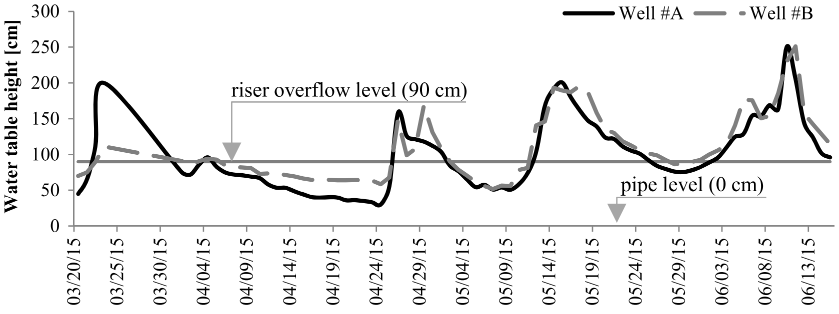

Figure 5. Water level at the drainage wells A (C-13 and 14) and B (C-15 and 16) in cm above the drain.

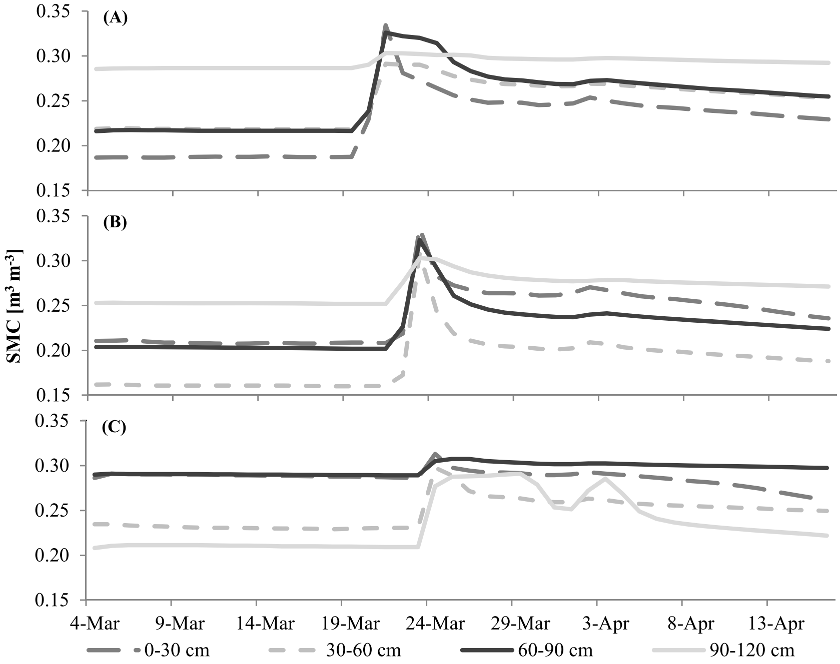

Figure 6. Dynamics of soil moisture content ($m^3\ m^{-3}$) during the second irrigation of winter wheat on phenological plots 1 (A), 2 (B) and 3 (C) in fields C-13 and 14.

(both vertical profile as well as spatial scale). Figure 6A shows that water for the phenological plot 1 was reached on 20 March at 3:30 pm (e.g. after 2 days) although the third vegetative irrigation started on 18 March. Hence, the SMC was raised from 18.8 to 20.0%vol at 30 cm depth soil profile with a maximum of 34.5%vol at 12:00 am on 21 March. Thereby SMC rise at the vertical profiles delays from upper soil (3:30 pm for 30 cm) to lower soil (6:30 pm for 120 cm). Consequently the applied irrigation water reached phenological plots 2 and 3 on 22 March (4:30 pm, Figure 6 B) and on 24 March (1:30 am, Figure 6C), respectively.

Groundwater table

The GWT measured by the CTD-10 sensor during the third irrigation of wheat is given in Figure 7. The graph shows that the groundwater levels tend to increase gradually, indicating a delayed response to the input of irrigation water from phonological plots 1 to 3. In fact, the maximum rise of the GWT (even though irrigation started 1–3 days before) was

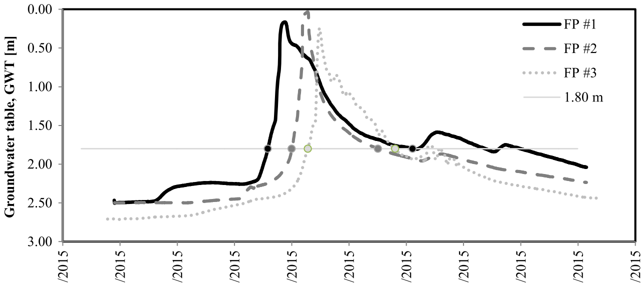

Figure 7. Accession and recession of the GWT during the second irrigation of winter wheat in C-13 and 14 measured using CTD-10 (30-min interval) in phenological plots 1–3 in 2015 (straight horizontal line is given for purposes of comparison). [Colour figure can be viewed at wileyonlinelibrary.com]

linked to with irrigation of the part of the field where the piezometers are located. During the third irrigation of wheat, in phenological plot 1 located at the midpoint between drains CHD-1 and CHD-2, the time it took the GWT to rise from 180 cm up to 20 cm was 1.5 days (excluding the irrigation start of 3 days), while it took 11 days to drop down to the initial level (180 cm) (Figure 7). Similarly, in the third irrigation of wheat in phenological plot 3 located at the mid-point of the drains such as CHD-2 as well as open drain OD-2, the time it took the GWT to rise from 180 cm up to 25 cm was 1 day (excluding the irrigation start of 3 days), while it took 6.5 days to drop down to the initial level (180 cm). In general, in the part of the phenological plots (1 and 3) located at the drain mid-spacing, the lag of GWL lowering is greater, i.e. this process is slower. Whereas it took 1.4 days (excluding irrigation duration of 3 days) to raise the GWT from 180 cm up to 3 cm and 6.2 days to drop down to 180 cm, i.e. the rate of drop is fourfold slower than that of rate of rise.

It may be noted that close up of the regulation structure during the irrigation in the observation well A at CHD-2 is prolonged GWT drop on 11 days at the mid-space of CHD-1 and 2. This enabled soil moisture to be maintained for longer periods. The duration of GWT drop was longer in phenological plot 5 in C-15 and 16 due to its location from the closed drain outflow at observation well B.

Mean GWT measured manually from 22 wells in C-13 and 14 and C-15 and 16 for the wheat-growing period is presented in Figure 8. The rise of GWT in the hydrograph indicates that all irrigations (including charging irrigation from 25 October to 11 November 2014, not shown) in both fields were concomitant with application dates (Table I). In addition, it can be seen from the hydrographs that two fields showed some delay of groundwater table peak during periods of high recharge (during irrigation events).

Water fluxes

The effect of the controlled drainage experiment was evaluated by comparing a ratio of the field parameters between transects A and B (1) versus B and the Srednekyzyltepa collector (2) along CHD-2 (Table III). The ratio of soil water content at the 1.2 m soil profile between (1) and (2) was 1.2, suggesting that the upper part of the field contained higher soil moisture for the crop to be utilized during the growing period compared with the lower portion of the field. Conversely, the ratio of the GWT between (1) and (2) was 0.78, indicating that the GWT in the upper portion of the field was 47 cm (22%) shallower than in the lower part (Table III). Thus, subsurface irrigation increased the moisture storage of the soil layer in the upper part of the field compared to the lower part.

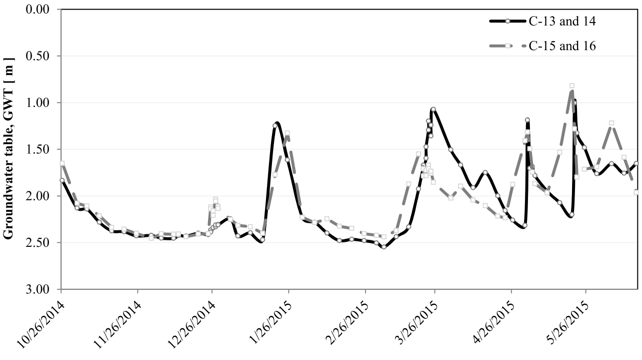

Figure 8. Dynamics of GWT during the wheat-growing period (averaged from 11 wells in each field).

The most important quantitative hydrological monitoring results are summarized in Figure 9. This graph presents the irrigation and precipitation amount, SMC, GWT and drainage amount at five phenological plots from 3 March to 15 June 2015. Although the third irrigation started on 18 March 2015, applied water (109 mm) reached phenological point 1 after 3 days, hence average weighted soil moisture at the 1 m soil profile and GWT rose from 22%vol to 32%vol and from 220 cm up to 27 cm, respectively (Figure 9A). Based on this graph, it can be noted that the soil moisture in phenological plot 5 (Figure 9D, between transects A and B) fluctuates less compared to other plots due to closed drainage outflow during the period. The average SMC during the study period (i.e. $\approx$ 0.31 m^3 m^{-3}) at maximum root zone distribution (90 cm) in phenological plot 5 (Figure 9D) was not much different from the average field capacity values (i.e. $\approx$ 0.30 m^3 m^{-3}). As was expected, the average root zone SMC under plots 3 and 5 (0.27–0.30 m^3 m^{-3}) was greater than those observed in plots 1 and 6 (0.24–0.25 m^3 m^{-3}), because of closed outflow of drainpipe CHD-2.

Table III. Average values of field parameters and their ratio between the upper part of the drained field (transects A and B) and the lower part (transect B and collector) measured from 3 March to 15 June 2015

Parameters	Statistics	Transects A and B (1)	Transect B and collector (2)	Ratio (1)/(2)
Soil water content at 0–120 cm soil profile	Minimum (mm)	220	117	1.88
	Maximum (mm)	355	356	1.00
	Mean (mm)	299	248	1.20
	Standard deviation (mm)	29.9	45.5	
	Coefficient of variation (%)	10.0	18.3	
GWT	Minimum (cm)	64.0	86.3	0.74
	Maximum (cm)	242	250	0.97
	Mean (cm)	164	210	0.78
	Standard deviation (cm)	38.0	35.7	
	Coefficient of variation (%)	23.3	17.0	

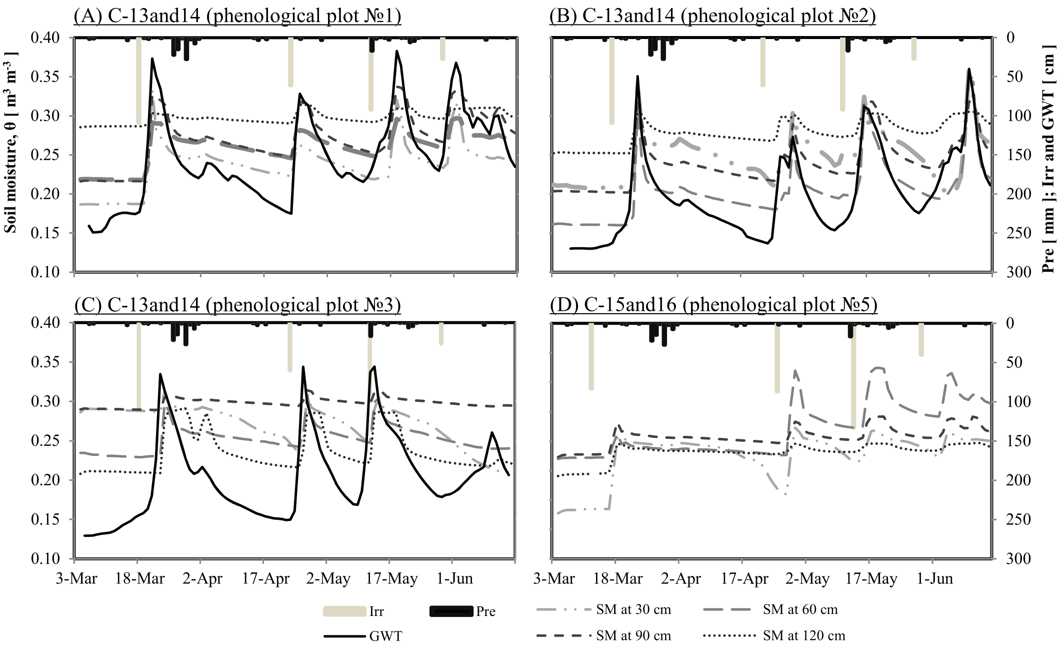

Figure 9. Combined results of hydrological measurements (Irr: irrigation, cm; Pre: precipitation, mm; GWT: groundwater table, cm; SM: soil moisture, $m^3 m^{-3}$) in phenological plots 1 (A), 2 (B), 3 (C), 5 (D). [Colour figure can be viewed at wileyonlinelibrary.com]

Crop yield

The yields and their components under different soil moisture conditions and GWT are presented in Table IV. The results suggest that the SMC had a notable effect on the yield of winter wheat (Figure 10A). However, a shallow GWT negatively affects grain yield (Figure 10B). It was consistent with the findings in other studies, which were under irrigation conditions (Karimov *et al.,* 2014). The maximum yields were 429 and 506 g m^{-2} in phenological plots 2 (average soil moisture content ≈ 0.24 m^3 m^{-3}) and 4 (0.34 m^3 m^{-3}), respectively. The root zone moisture content in phenological plots 1 (≈ 0.26 m^3 m^{-3}) and 3 (≈ 0.27 m^3 m^{-3}) produced lower yields (Table IV).

Table IV. Wheat yields under mean soil moisture content and groundwater table from 3 March to 15 June 2015

Parameters	Phenological plots						
	1	2	3	4	5	6	7
Grain yield (g m^{-2})	276	429	298	506	434	465	356
Soil moisture content (m^3 m^{-3})	0.26	0.29	0.27	0.34	0.30	0.28	0.31
GWT (cm)	154	201	197	N/A	163	210	157

N/A: no information was available.

CONCLUSION

Our experimental set-up produced valuable insights into the hydrological effects of controlled drainage. The introduction of a control structure on subsurface drainage at the monitoring well resulted in relatively taller crop height at the maturity stage of wheat (79.5–104 cm) in plots 2, 4 and 5 (along

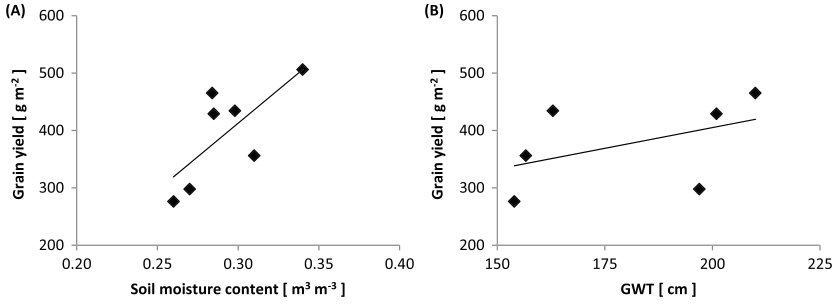

Figure 10. Wheat yield trend in the seven phenological plots under average SMC (A) and GWT (B).

the CHD-2), whereas plant root depth was shallower (59–64 cm) at these plots compared with those in plots 1, 3 and 6. It can be concluded that root depth at the plots beside the CHD-2 line penetrated deeper due to the increase in GWT depth. In contrast, the lower root depth of plots 2, 4 and 5 mainly resulted from the GWT restricting downward penetration of the root system.

It can be concluded that the rise of the SMC is concomitant with that part of the field where irrigation water reaches (both vertical profile as well as spatial scale). Therefore the maximum rise of the GWT (even though irrigation started 1–3 days before) is also concomitant with irrigation of the part of the field where the piezometers are located.

This study suggests that it is possible to control the GWT depth at monitoring wells. However, operating open drains and collector systems as well as the existence of sand and sand-gravel layers in the soil profile where the subsurface drainage is installed had a greatest impact on maintaining GWT. Hence, it is difficult to manage irrigation and drainage systems on larger fields to control GWT and assess its impact on maximizing crop yield. Nevertheless, this study is helpful for managing irrigation and controlingl shallow GWTs. The results of the study can support the first view of controlled drainage studies that provide good short-term returns in the form of higher crop yields due to reduced water deficiency stress.

Based on the findings from this experiment, the following recommendations can be highlighted:

- a new approach (e.g. an integrated irrigation and drainage water management system) is needed in order to apply controlled drainage management. This implies interactivity between operation of the irrigation system and management of the drainage system. In this instance, the drainage system will be managed in order to control the flow and GWT depth in the course of time in response to irrigation management and percolation;
- control of the GWT at the inspection sump is possible using a manually developed PVC riser, but it is only feasible in flat lands because of the alignment of the subsurface drains relative to the grade of the field surface. Careful selection of a proper drainage site is a prerequisite for practising CTD. For CTD to be effective, the soil texture under the site selected has to be more or less homogeneous, with less or no sand and sand-gravel layer near the control structure. In addition, one has to be sure that the drainage pipe has no perforations near the control structure in the monitoring sump. This implies consideration of structures in future for the control of the position of the GWT in new subsurface drainage system design;
- careful monitoring of all water balance components and irrigation water management will be required when implementing CTD.

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