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The soil–water flow system beneath a cotton field in arid north-west China, serviced by mulched drip irrigation using brackish water

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Abstract A field experiment was carried out in southern Xinjiang, China, to reveal soil-water flow pattern beneath a combined plastic-mulch (film) and drip-irrigation system using brackish water. The soil-water flow system (SWFS) was characterized from soil surface to the water table based on observed spatio-temporal distribution of total soil-water potential, water content and electric conductivity. Root suction provided a strong inner sink. The results indicated that SWFS determined the soil salinity and moisture distribution. Drip-irrigation events could leach excess salts from the root zone and provide soil conditions with a tolerable salinity level that supports the growth of cotton. High-salinity strips were formed along the wetting front and at the bare soil surface. Hydrogeology conditions, irrigation regime, climate, plant growth and use of mulch would affect potential sources and sinks, boundary conditions and the size of the SWFS. At depth 0–60 cm, the soil salinity at the end of the irrigation season was 1.9 times that at the beginning. Beneath the mulch cover, the soil-water content in the ‘wide rows’ zone (55 cm between the two rows with no drip line) was higher than that in the ‘narrow rows’ zone (15 cm between the two rows with a drip line) due to the strong root-water uptake. The downward water flow below the divergent curved surface of zero flux before irrigation, and the water-table fluctuation with irrigation events, indicated that excessive irrigation occurred.

Keywords China · Arid region · Agriculture · Salinization · Water potential

Introduction

Water shortage and soil salinization are the two critical problems affecting sustainability of the agriculture in arid regions (Chen et al. 2010a; Danierhan et al. 2013). Over 50 % of river water is developed for the purposes of irrigation in Xinjiang, north-west China, and more than 70 % of the developed rivers are inland (Li 2003). Many rivers and lakes are dried up at the lower reaches, which is as a result of water diversions in the inland river basins; thus, desertification is expanding (Li 2003). Drip irrigation has been widely used for saving water and increasing water-use efficiency by reducing evaporation and deep percolation in arid regions (Sezen et al. 2006; Vazquez et al. 2006; Assouline et al. 2006; Marouelli and Silva 2007; Bhattarai et al. 2008; Liu et al. 2012; Panigrahi et al. 2013; Selim et al. 2013). “Mulched drip irrigation”, which is a method that combines the use of drip irrigation and plastic film (mulch) applied at the land surface, has been used widely in Xinjiang since the early 1990s and was applied to over 15.3 million ha in 2009 (Liu et al. 2012); however, only 0.5 % of the total cultivated land is drip-irrigated area in China, compared with the world average of 1.5 % (Niu et al. 2010).

Irrigation with water that has elevated salinity provides another possibility to meet increased water demands (Oron et al. 2002; Letey et al. 2011). Shallow brackish water with total dissolved solids (TDS) of 2–3 g/L is distributed widely throughout north and north-west China, where freshwater is in shortage. The quantity of brackish water that can be used for agriculture is about 13 billion m^3 (Yang and Cheng 2004). In Xinjiang, drip irrigation for cotton, a highly salinity tolerant plant, with brackish water is increasing (Chen et al. 2010a). Mulched drip irrigation with brackish water has been a new field practice (Wang 2013; Wang et al. 2014a). Arid regions are susceptible to high risk of salinization, which is mainly caused by the high evaporation rates as well as the retarded leaching characteristics of the soils in these areas. Irrigation is a major factor affecting soil salinity, and salts enter into the soil through applied water and accumulate in the root zone because of inadequate leaching (Mirjat et al. 2014). In addition, excessive irrigation can lead to a rise in the water table. Salinity levels can increase due to the upward salt flux when groundwater is shallow (Hamed 2008).

For drip irrigation systems with plastic mulch, when irrigation water drips into the soil, it undergoes several processes. Some water gets absorbed by plants through their roots, and then escapes from the leaves to the atmosphere as transpiration; some gets stored for use by

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the plant; and finally some may percolate into groundwater or evaporate from a bare soil surface. A number of studies have described the movement of soil water and dissolved salts in soil profile under drip irrigation. Treatments with and without plastic mulch have significant effects on soil water and salinity distribution (Selim et al. 2013; Kirnak and Demirtas 2006). The wetting patterns of drip irrigation depend on several factors including the drip-line and dripper placement, soil texture, root-water uptake, irrigation intensity, and initial water content (Cook et al. 2003; Kirnak and Demirtas 2006; Zumr et al. 2006; Hao et al. 2007; Shan et al. 2011; Danierhan et al. 2013; Wang et al. 2014b). Bar-Yosef and Sheikholslami (1976) found that the soil water was prone to expanding in the vertical profile of sandy soil under drip irrigation. Danierhan et al. 2013 investigated the effects of different dripper discharge rates on salinity distribution. After drip irrigation in experiments for 3 and 7 years, Zhang et al. (2013) found that salts got accumulated within 0–40 and 40–80 cm depths of soil layers respectively, when drainage systems were incomplete. The single line design is more efficient at leaching salts than the double line design because more water flows out of each dripper for every irrigation event (Wang et al. 2014b). Numerical simulation can be an effective tool for assessing water flow and salt movement associated with drip irrigation (Liu et al. 2013a; Selim et al. 2013; Wang et al. 2014a). Based on field experiments of mulched drip irrigation using brackish water on cotton, Wang et al. (2014a) found that the soil salinity increased during the growing season but flood irrigation after harvesting leached the accumulated salts and returned the salinity to background levels. Numerical simulations extended for 20 years concluded that mulched drip irrigation using alternately fresh and brackish water during the growing season, and flood irrigation with freshwater after harvesting, was a sustainable irrigation practice that would not lead to soil salinization (Wang et al. 2014a). Nevertheless, the above research has not described the schematic distribution of total soil-water potential (H), which can be used to account for the mechanisms of flow patterns and water and salt distribution.

This report aims to reveal the mechanisms of soil-water and salinity distribution under drip irrigation with brackish water. The experiments were carried out in southern Xinjiang, north-west China. Based on the schematic distribution of total soil-water potential, the concepts and characteristics of the soil-water flow system (SWFS) under mulched drip irrigation (and their controlling factors) are presented. The conclusions may contribute to guidelines for optimum soil-water and salt management under mulched drip irrigation with brackish water.

Materials and methods

Details of field experiment

The field experimental site is located in an alluvial plain of the Peacock River, Tarim basin, in the arid southern part of Xinjiang (Fig. 1). The land surface elevation is about 901 m above the mean sea level. It is classified as a continental desert climatic region with an average annual precipitation of only 58 mm. During the cotton-growing season from April to October 2012, the precipitation was 43 mm; the potential evapotranspiration was 945 mm; the sunshine time was 2,229 h; the mean wind speed was 1 m/s although the highest wind speed was 14.8 m/s; and the mean, the highest and the lowest temperatures were 21, 36, and −5 °C, respectively.

The experiment was conducted from 8 April 2012 to 5 October 2012 and the cotton field was about 2 ha in size. Cotton seeds were sowed on 4 May 2012. There were 29 mulches in the experimental field, whereby the width of each plastic mulch was 110 cm, and the no-mulch strips between pairs of mulches were 40 cm wide. The wide-rows zone, narrow-rows zone and no-mulch zone are defined (in Fig. 2) according to the location of the cotton plants. Drip lines of the experimental field were set at the mode of “one mulch, two drip lines and four rows” (Fig. 2a), which indicated that two drip lines, beneath the mulch, were each in the middle of a narrow-rows zone. The spacing between drippers along the line was 30 cm. The drip-line arrangement of “one mulch, one drip line and four rows” indicated that one drip line, beneath the mulch, was in the middle of the wide-rows zone (Fig. 2b). The experiences of the farmers showed that the “one mulch, two drip lines and four rows” mode was more suitable than the “one mulch, one drip line and four rows” mode for a loamy field. The “one mulch, two drip lines and four rows” mode, which was the only style in the experimental field, could conveniently provide irrigation water for roots and reduce deep percolation. The electrical conductivity (EC) of the brackish water used for irrigation was 2.8–3.1 mS/cm. The total quantity of irrigation water applied during the entire growing season was 525 mm. Each irrigation event lasted a few hours. A 5-day irrigation-event frequency was applied after starting the drip irrigation, and the discharge rate was about 2.5 L/h for a dripper, which is the usual irrigation practice for cotton in this area. The irrigation events were managed by farmers, and the actual schedules and amounts of irrigation water are given in Table 1. Soil texture, which was relatively homogeneous, was loam in the experimental field. The bulk density was 1.63 g/cm^3 and texture percentages of sand, silt and clay were 46.81, 45.96 and 7.23, respectively. The return flow of irrigation water seeped into the drainage channel. The lower boundary and the average water level of the drainage channel were about 2 and 1.8 m to land surface during irrigation season, respectively (Fig. 2c).

Measurements

The measurement locations are shown in Figs. 2 and 3.The matric potential of the soil water was measured using tensiometers (WDS-15, Meiwantong Ltd., Wuhan, China) at different depths down to 130 cm, in the wide rows, narrow rows and bare soil strip (no mulch). The

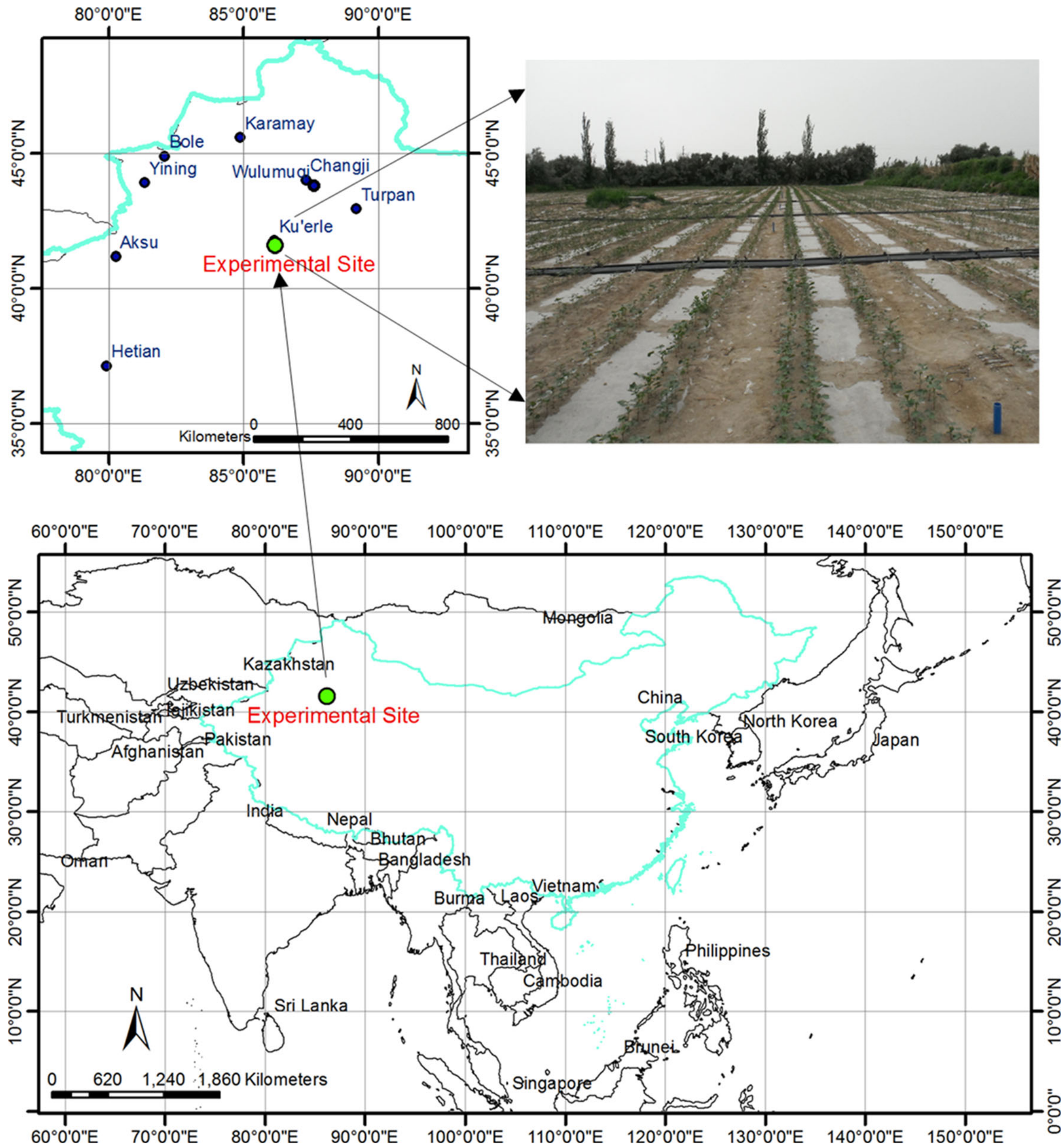

Fig. 1 Location of the experimental site

soil-water retention curve of an undisturbed soil core was also measured. Soil-water content (θ) was monitored in-situ using an L520 Neutron Probe (Institute for Application of Atomic Energy, JAAS, Nanjing, China), but the topsoil was monitored using an MPM-160 moisture probe (Meridian Measurement Pty Ltd., Narrabri, Australia). In addition, the distribution of the water content (θ) and pore-water electrical conductivity (EC_p) were measured using a calibrated WET sensor (Delta-T Devices Ltd., Cambridge, UK) from soil surface to a depth of 60 cm, 48 h after the 13th irrigation (Fig. 3c).

Soil water was extracted using the Rhizon Soil Moisture Samplers (Eijkelkamp Agrisearch Equipment Co., Giesbeek, Netherlands) at different depths in the field (Fig. 3c). The EC of the soil water, which indicated the level of soil salinity, was measured with a conductivity meter (DDS-307, INESA Scientific Instrument Co., Ltd., Shanghai, China).

The tensiometers and soil moisture samplers were actually placed at different vertical planes along the drip line to ensure enough space for each measurement. The H and EC of the surface soil (depth of 0 cm) was assumed to be equal to the values at depth of 10 cm, due to the difficulties of measuring the matric potential and EC for surface soil water.

A monitoring room was located in the field to observe soil-water potential and obtain the soil-water samples. Beside the room, there was a weather station and a monitoring well, which was drilled to measure the dynamic of the water table and groundwater quality. A Davis wireless Vantage Pro2 weather station (Davis Instruments, California, USA) was used to observe the

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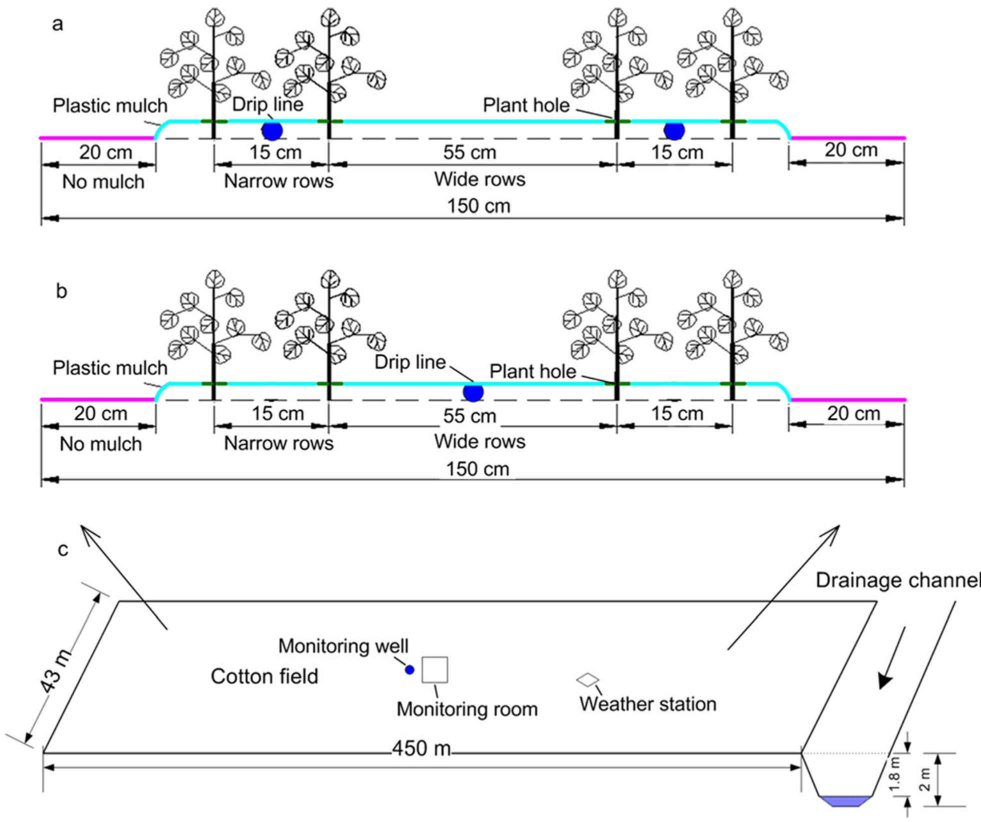

Fig. 2 Planting and drip-line arrangements in the cotton field, **a** "one mulch, two drip lines and four rows" mode, **b** "one mulch, one drip line and four rows" mode and **c** cotton field with a drainage channel

microclimatic factors such as light intensity, air temperature and humidity, wind speed and direction, dew point, barometric pressure, precipitation and solar radiation.

The weather station had been in use at the site for several years. The other instruments were installed between 12 May 2012 and 30 June 2012. The matric potential, water quality and water table were measured every 5 days 24 h before the *start* of each irrigation event and 24 h after the field irrigation *stopped*. Groundwater and soil-water samples were also extracted at the same time. The weather station recorded hourly climatic information of temperature, pressure, humidity, wind speed, solar radiation and wind direction. A typical irrigation event at the bolling stage, i.e. the 11th irrigation event, was chosen to obtain the detailed dynamics of matric potential, water content and EC of soil water. These measurements were carried out 24 h before and 2 h after the irrigation event started, just after the irrigation and 24 h after the irrigation stopped.

The van Genuchten and Mualem models were used to predict the soil-water retention curve and hydraulic conductivity based on experimental data, as shown in Fig. 4 by RETC software (Mualem 1976; van Genuchten 1980; van Genuchten et al. 1991). In general, the solute and soil-water temperature were not considered in calculating soil-water transport (Hanson et al. 2006a; Hammecker et al. 2012; Liu et al. 2013a); thus, the H consisted of matric and gravitational potential in this study, and the soil surface was the null point with the upward direction for calculating gravitational potential.-Surfer software was used to draw the contour maps showing H, θ and EC.

Results and discussion

Soil-water potential

Mulched drip irrigation is a combination of drip irrigation and mulching. Drip irrigation can regulate amounts of irrigation water and reduce deep percolation; plastic film mulch is always used to prevent evaporation and regulate temperature (Liu et al. 2012). Figure 3a,b shows the

Table 1 Schedule and amount of irrigation water applied

Date	Amount (mm)	Irrigation event
30 June 2012	28.6	11:00–13:00
5 July 2012	22.9	10:00–12:18
10 July 2012	17.9	9:00–10:50
15 July 2012	30.3	10:05–13:00
20 July 2012	52.7	9:05–13:10
25 July 2012	44.7	8:00–13:30
31 July 2012	45.9	8:00–12:36
5 August 2012	44.7	9:25–14:03
10 August 2012	47.1	8:25–13:05
15 August 2012	45.6	11:50–16:30
20 August 2012	45.0	14:00–17:36
25 August 2012	38.8	10:12–13:05
30 August 2012	30.1	9:30–12:10
5 September 2012	31.0	10:28–13:55

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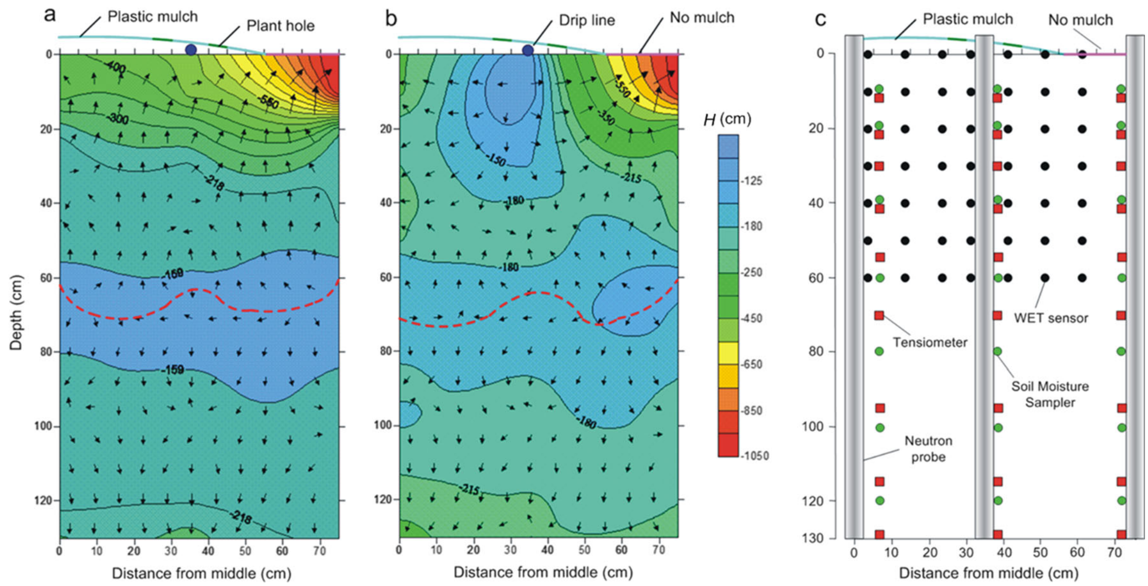

Fig. 3 Distribution of measured total soil-water potential (*H*) **a** 24 h before, **b** 2 h after the 11th irrigation starts, and **c** locations of different measurements. *Red dashed lines* indicate a curved surface of zero flux (CSZF) (**a**–**b**)

spatial distribution of measured *H* in the soil profile perpendicular to the drip line, 24 h before and 2 h after the 11th irrigation event started, when the cotton was at the bolling stage. The 11th irrigation event represented a typical irrigation process. Hydraulic gradient controlled the direction of soil-water movement. It was clear that there was a divergent curved surface of zero flux (CSZF) in the profile, i.e., water above the CSZF moved upward and water below the CSZF moved downward (Fig. 3a,b). The CSZF resulted from the irrigation events. Its position and shape could be affected by soil heterogeneity, root distribution, evaporation from bare soil and plant holes, planting and drip-line arrangements, and water-table depth. Figure 5 shows the total soil-water potential distribution on different dates when the CSZF was not yet in existence. The dates 25 June 2012 and 23 September 2012 represented the typical days for a before and after irrigation season with the water-table depths of 1.98 and 2.05 m, respectively. The day of 19 July 2012, with the water-table depth of 1.83 m, was the fourth day after an irrigation event in the irrigation season, and the amount of irrigation water was 30.3 mm, which is relatively small; however, the CSZF significantly existed on 19 August 2012, which was the fourth day after the tenth irrigation event, with the applied water of 45.6 mm as shown in Fig. 3. From the preceding, it could be concluded that when the applied water was less, or when no irrigation happened, some of the groundwater might be evaporated through the soil profile because of the soil evaporation and capillary rise. During the period with large amounts of irrigation water, the CSZF might exist between the irrigation events, and soil-water flow below the CSZF was downward to the groundwater. It was noted that above the depth of 20 cm (see Fig. 5), the *H* of 19 July 2012 was higher than those of 25 June 2012 and 23 September 2012; however, at the depth of 40–70 cm, the *H* of 19 July 2012 was significantly lower than those of 25 June 2012 and 23 September 2012. The reason might be

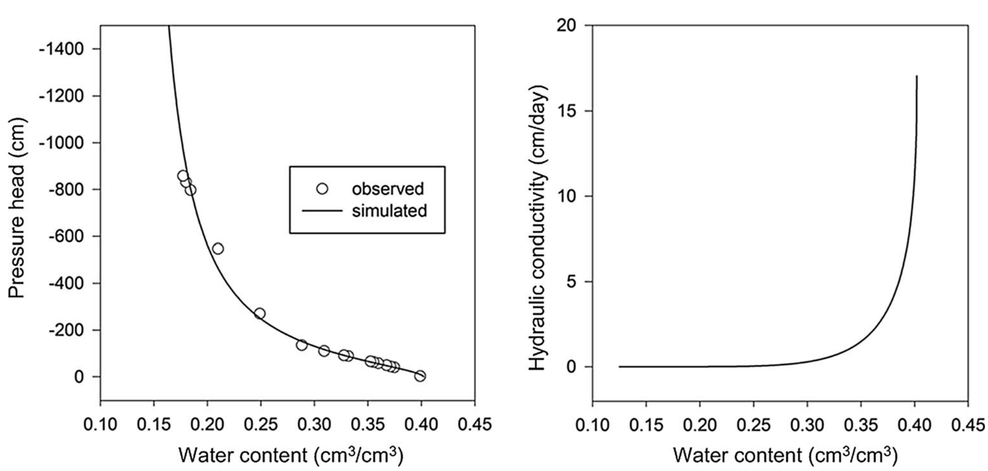

Fig. 4 Soil-water retention curve and hydraulic conductivity as a function of water content

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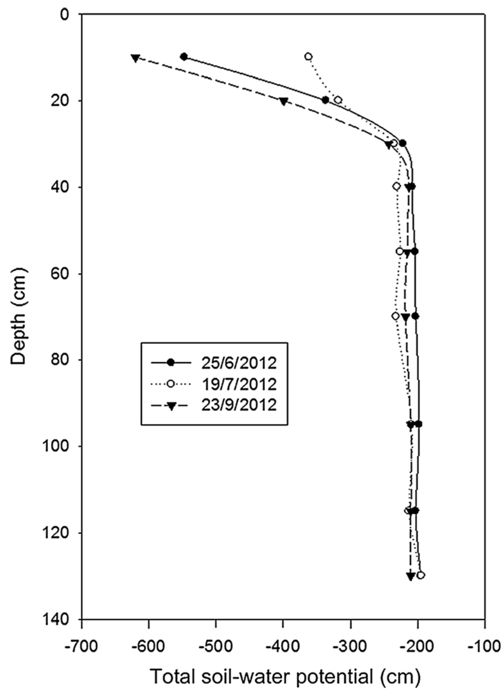

Fig. 5 Total soil-water potential (*H*) distribution of the soil profile in the narrow-rows zone on 25 June 2012, 19 July 2012 and 23 September 2012

that the root-water uptake was strong and plastic mulch could prevent soil evaporation at the flowering stage.

The CSZF was between depths 60 and 70 cm for the 11th irrigation at the bolling stage. The dynamic of water flow was relatively complex above the CSZF compared with that below the CSZF. Before irrigation event, water above the CSZF moved towards the root zone, plant holes and bare soil strip (no mulch) due to root-water uptake and evaporation from the soil. However, a downward water flow below the CSZF before irrigation indicated that deep percolation and recharge to groundwater happened. During irrigation (2 h from irrigation event start), the highest *H* was at the dripper and decreased with increasing distance from the drip line; water flow was from the drip line to the wetting front. The *H* decreased around the drip line, but increased near the bare soil strip after irrigation event.

SWFS of mulched drip irrigation

Based on the schematic distribution of the measured *H* (Fig. 3), Fig. 6a,b shows the flow nets or flow patterns of the flow domain 24 h before and 2 h from the 11th drip irrigation start, respectively. Due to the small precipitation-evaporation ratio (4.5 %), precipitation was neglected. The pattern of the SWFS under mulched drip irrigation was characterized by a relatively homogeneous medium. Most of the time it was unsaturated, but during the irrigation events, downward moving pockets of saturated flow were formed temporarily, depending on the amount of the irrigation flux and soil hydraulic conductivity (Hao et al. 2007). Such pockets were depleted as a result of root-water uptake and downward movement of water against the hydraulic gradient (Boaga et al. 2013). The upper boundary of the SWFS with the sources and sinks from left to right were: strong line sink of evaporation from bare soil strip, impermeable-sheet boundary with a very weak evaporative point sink at plant holes, and a periodic strong drip irrigation point source. Irrigation conditions, climate, cotton plants and plastic film mulch were variable; thus, sources and sinks of the upper boundary were complex. The lower boundary was the water table, which was subject to fluctuation at the onset of an irrigation event or lateral flow of groundwater. Groundwater could be the source of the SWFS due to capillary rise of phreatic water and the sink of the SWFS due to gravitational downward percolation. Two sides of the flow domain on the cross-section, perpendicular to the drip line, were fixed and considered as no-flow boundaries. The *H* decreased from the potential sources to sinks. Root-water uptake provided a strong sink, and soil-water storage or consumption provided a sink or source in the flow domain.

The SWFS of mulched drip irrigation determined the distribution of water content and EC as shown in Figs. 7 and 8. The wetting shape of a semi-ellipsoid was formed and expanded from the drip line to the wetting front during the drip irrigation event. Above the CSZF, water content changed dramatically because of the irrigation event, root-water uptake and evaporation from bare soil. Below the CSZF, the water content was high because of the downward water flow and capillary rise of groundwater. The lowest water content was near the bare soil strip.

Roots took up some dissolved elements or nutrients selectively, but the bulk of the other dissolved salts were not absorbed. Therefore, root-water uptake increased the concentration of the resultant salt around and near the roots. The drip irrigation event could save water and remove the excessive salt to ensure a tolerable level for cotton growth; however, in a certain field with the defined amount of irrigation water and frequency, the limited irrigation depth and evaporation of bare soil resulted in a high-salinity strip along the wetting front and near the bare soil surface. The total soil salt content consists of resident soil salt (background) and the solute from irrigation water and capillary rise of groundwater. In the study by Mai et al. (2013), the salt was found to accumulate below the tillage layer due to phreatic water evaporation. When the applied water was decreased, cotton uptake of the shallow saline groundwater increased (Hanson et al. 2006b). Soil salt was leached out of the root zone, and accumulated around the drip line because of no field-wide leaching (Hanson et al. 2006b).

Maas and Hoffman (1977) noted that the threshold of irrigation-water salinity for cotton yield was 7.7 mS/cm; however, this threshold salinity was expressed by the electrical conductivity of saturation extracts (EC_e). Different measurement methods may have various threshold values. The root length was affected when soil EC (water/soil 1:1) exceeded 2.8 mS/cm (Mai et al. 2013). The soil salinity in work described in this report was the EC of soil

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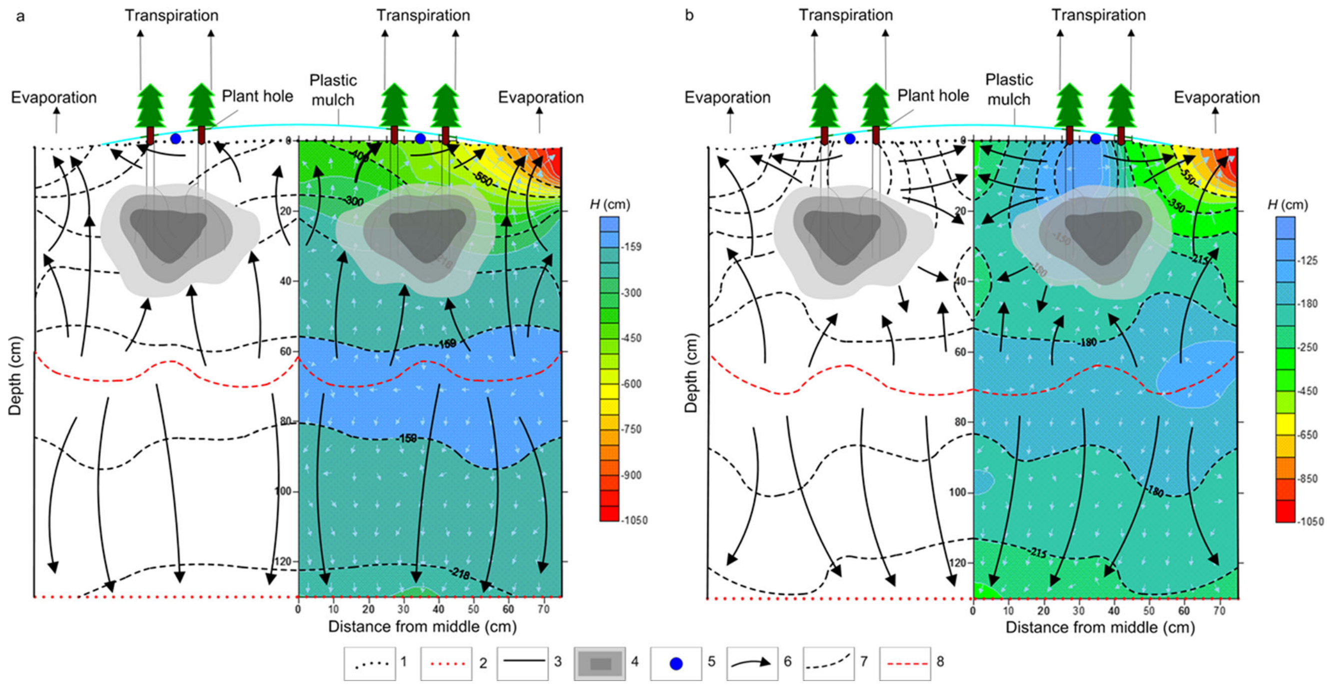

Fig. 6 SWFS of mulched drip irrigation **a** 24 h before and **b** 2 h from the 11th irrigation start. Legend: *1* soil surface; *2* the lower depth of the observed profile; *3* no-flow boundary; *4* root-water uptake (the *dark grey* indicates larger root density); *5* drip line; *6* flow line; *7* equipotential line; and *8* CSZF

water, which was extracted directly from the soil profile, and the salt concentration was higher than that of saturation extracts; thus, Fig. 7 shows the distribution of relatively high EC in the soil profile. Many factors might influence the salinity threshold for plant growth such as growth stage, plant variety and rootstock, soil water and aeration, fertility and climate (Maas and Hoffman 1977). The threshold for cotton growth can be improved by

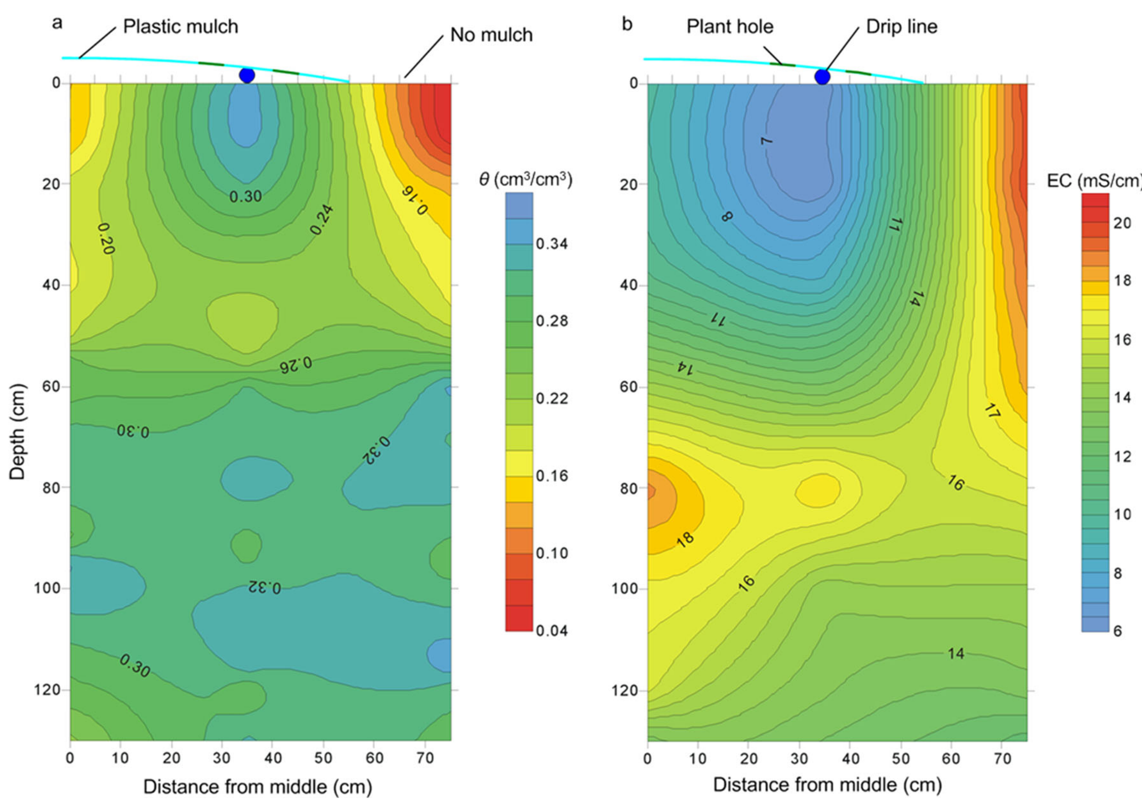

Fig. 7 Distribution of **a** water content (θ) 2 h from the 11th irrigation start and **b** EC of soil water just after the 11th irrigation event

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fertilizer application at low to moderate salinity (Chen et al. 2010b). Salts in irrigation water may reduce the cotton growth but the trace elements, to a certain degree, may be beneficial for growth. In the study by Wang et al. (2014a), cotton irrigated with brackish water had a higher yield at the maximum threshold salinity (EC_e 20 mS/cm) than cotton irrigated with freshwater due to the effects of trace elements.

It was obvious that the regime of salt accumulation at the surface layer was not sustainable for agriculture because of soil salinization. Thus, flood irrigation with freshwater could be applied to flush the accumulated salt out of the soil profile before sowing or after harvesting. The depth from soil surface to groundwater was about 3.3 m before flood irrigation in spring. During the flood irrigation, groundwater level increases due to the return flow. The leached salt in the flood-irrigation return flows to the drainage channel (Fig. 2c), which was about 2.0 m below the soil surface (and could also control the water table), was finally concentrated in a salt wasteland far downstream from the cultivated land. For the mulched drip irrigation with brackish water scenario at the experimental site, the EC of soil water in the root zone increased substantially after harvesting until the flood irrigation phase. In the study by Wang et al. (2014a), flood irrigation leached most salts out of the root zone and the EC decreased again to background levels. Thus drip irrigation with brackish water during the growing season and flood irrigation with freshwater after harvesting or before sowing were feasible strategies for saving water and avoiding salinization.

Figure 8 shows the contour lines of water content and EC_p. The lowest water content, in the center, was consistent with the largest density of the root-water uptake. The root-water uptake region could expand due to transpiration after the irrigation events. A new drip irrigation event could make the root-water uptake region shrink temporarily and then transpiration could expand the root-water uptake region again. Lower EC_p values were observed in the depth zone 5–15 cm below the drip line. The salt was leached out of the root zone and accumulated at the wetting front, forming the higher soil salinity. The higher soil salinity of the topsoil was due to the evaporation at the naked soil surface and plant holes. It should be noted that because of the different techniques and the spatial variability of field soil salinity, there were significant differences in soil salinity between the EC just after the 11th irrigation event shown in Fig. 7b and EC_p measured by the WET sensor 48 h after the 13th irrigation shown in Fig. 8b. However, both figures show the similar law of salt transport controlled by SWFS of mulched drip irrigation.

Controlling factors of the SWFS

The SWFS of mulched drip irrigation is controlled by five components: hydrogeology conditions, irrigation, climate, plant and plastic film mulch. Each component is associated with various parameters. For instance, the hydrogeology component includes the depth of the water table, groundwater quality, field lithology and salinity characteristics of the soil profile. The irrigation component includes the combination of drip lines and dripper spacing, the discharge rate, irrigation water quality, irrigation duration and frequency. The climate component includes temperature, seasonal variations of precipitation, potential evaporation, etc., whereas the plant component includes the distribution of plants (spacing between rows and in-row) and the growth stage.

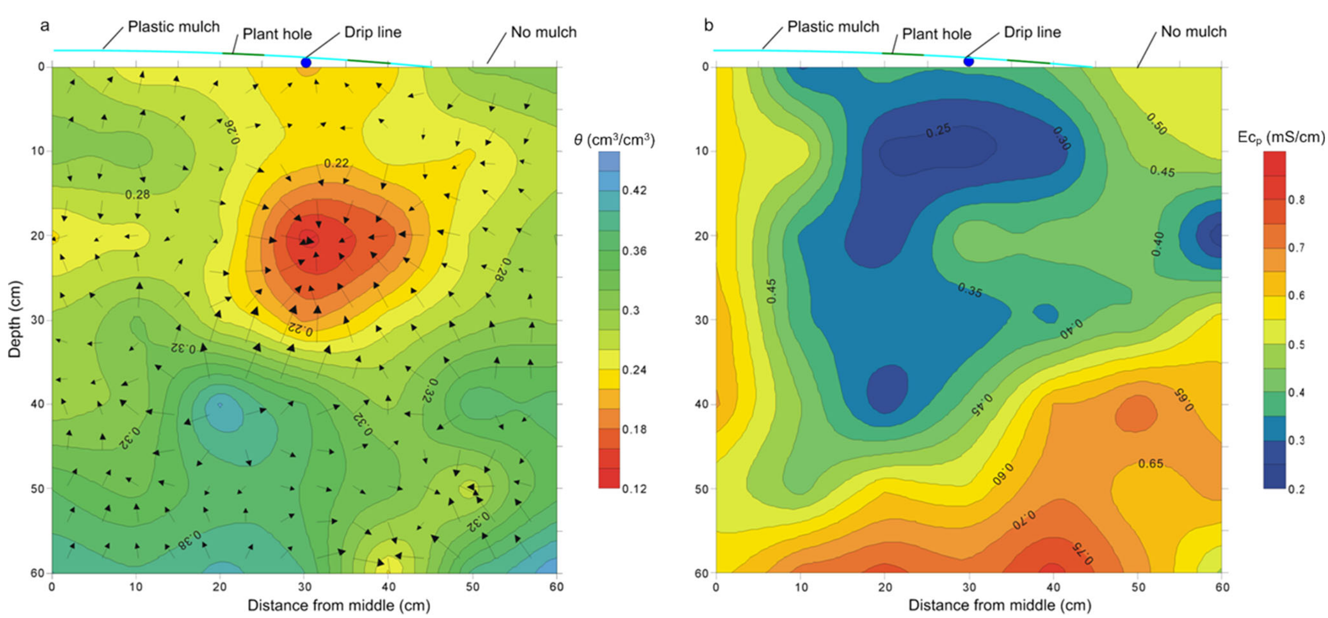

Fig. 8 Distribution of **a** the water content (θ) and **b** EC_p measured by the WET sensor in a soil profile 48 h after the 13th irrigation, 1st September 2012

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Hydrogeology conditions
Soil salinity of the root zone is affected by the depth to the water table and salinity of the shallow groundwater (Hanson et al. 2009). Since the salinity of shallow groundwater was higher than that of the irrigation water in the study area, an appropriate management strategy of the SWFS should reflect less evaporation of soil water and groundwater, and rational leaching of soil salinity. However, the depth of the water table and the EC of the groundwater (EC_g) at the experimental site showed a significant response to the drip irrigation events, i.e. rising water table during the growing season and increasing EC_g after the final drip irrigation. The subsequent reduction of water supply caused water-table decline and EC_g increase due to the decrease of deep percolation and natural drainage of groundwater (Fig. 9). With the depth to water table increasing, while other conditions remain the same, the scope of the SWFS expands due to the increasing distance from the upper to the lower boundary. Soil plays a crucial role in the water cycle for conveying and partitioning water flux (Schlueter et al. 2013). Wet pockets in sandy soil are characterized as vertical elongation, and show as horizontal elongation in light clay soil (Hao et al. 2007). The structural heterogeneity of the surface soil has a great effect on the spatial distribution of evaporation, and the root distribution also adapts, to some extent, to the heterogeneity (Schlueter et al. 2013). The root growth is also effected by soil types. In the study by Preti et al. (2010), while the evaporation/precipitation ratio was large and the soil was clay, roots were prone to be closer to the soil surface.

Irrigation
Combinations of drip lines and dripper spacing are very important factors influencing the SWFS. For example, the SWFS for the mode of "one mulch, one drip line and four rows" (M_1; Fig. 2b) is significantly different from that of "one mulch, two drip lines and four rows" (M_2; Fig. 2a). Spatial patterns of the potential source at the dripper are mainly controlled by the irrigation modes. The one drip line under the mulch is the single potential source of SWFS, while two drip lines would be the double potential sources of SWFS. Soil-water content of the narrow-rows zone and no-mulch zone for the M_2 mode was higher than that of the M_1 mode (Liu et al. 2012). The M_1 mode was previously used (a few years ago) at the experimental site but it could not supply enough irrigation water for the cotton rows beside the bare soil strip. M_2 is now the main irrigation mode for the sandy or loamy soil of the study area. For the silty loam, the M_1 mode was more efficient at salt leaching than the M_2 mode because more water flowed out at each irrigation event (Wang et al. 2014b).

Irrigation frequency and water quality affect the distribution of soil-water content, soil salinity and crop water consumption. Cotton yield decreased with the decrease of irrigation frequency (Liu et al. 2013b). El-Hendawy et al. (2008) reported that soil-water content and retained soil water, depending on soil depth, were affected by the drip irrigation frequency. Irrigation with freshwater produced a larger transpiration rate than irrigation with saline water because of the lower root-water uptake (Yang et al. 2010). During the growth season with drip irrigation, the salts mainly accumulated at depth 0–60 cm of the silty clay loam (Liu et al. 2013b). A greater dripper discharge rate with longer irrigation duration would enhance the potential source at the dripper. As concluded by Hao et al. (2007), the size of the wet pocket is determined by the specified discharge rate of the dripper.

Serious salinity problems in the root zone may be the result of shallow saline groundwater, low irrigation-water quantity, intense evapotranspiration, or a long time interval between two irrigation events. Figure 10 shows that the soil salinity increased drastically during the first month of the irrigation season, from less than 5 mS/cm to a maximum of 10.1 mS/cm, and decreased slightly at the later stage. At the early stage of the irrigation season, the soil salts accumulated at the surface soil layer because of the capillary rise of groundwater, strong root-water uptake and soil evaporation. With increasing application of water, the extent of salts accumulation was restricted and reached maximum at the bolling stage. The downward water flow below the CSZF before irrigation (Figs. 3a and 6a), and the water-table fluctuation during the two irrigation periods (Fig. 11) indicated that groundwater was recharged and excessive irrigation occurred. Thus, some of the salts at the surface layer were leached into the deeper soil layer and

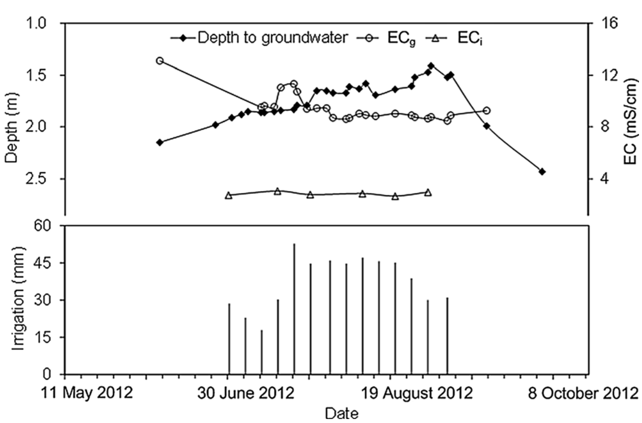

Fig. 9 Drip irrigation and the water-table fluctuations and EC of groundwater (EC_g); EC_i indicates EC of irrigation water

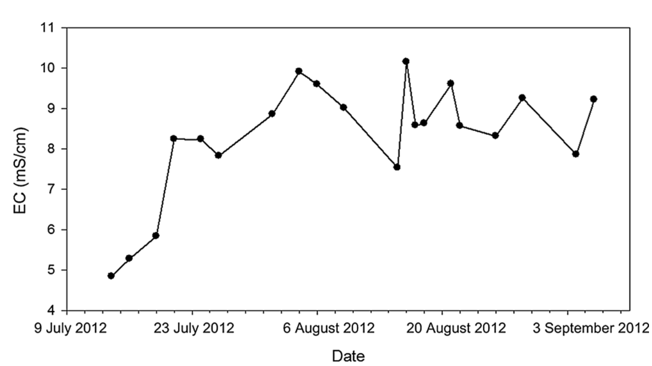

Fig. 10 Dynamic of the soil salinity at the depth of 0–60 cm during the irrigation season

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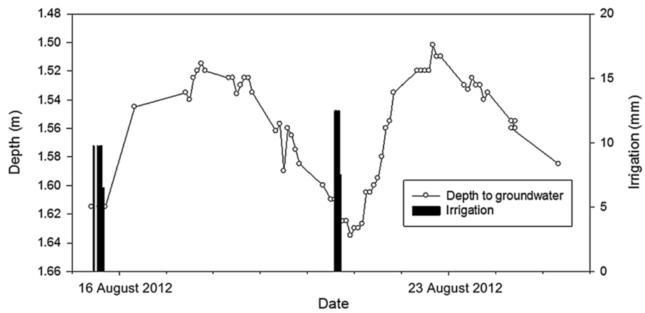

Fig. 11 Water-table fluctuation during the two irrigation periods (15–25 August 2012)

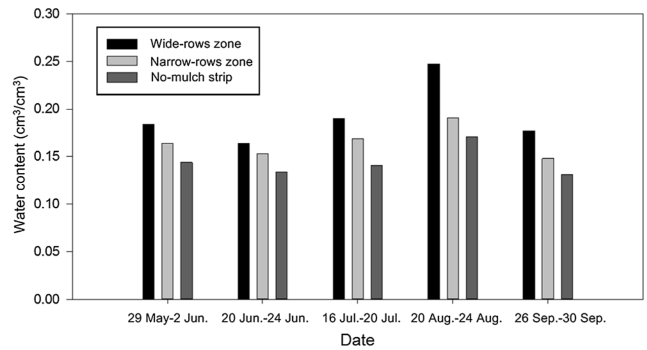

Fig. 13 Water content of different positions at a depth of 0–25 cm during the irrigation season in 2012

groundwater, and the soil layer of 0–60 cm kept a rough salt balance in August. It can be concluded that irrigation with larger amounts of brackish water may not only accumulate salts but also leach the salts to some extent; however, salinity of the surface soil layer of 0–60 cm at the end of the irrigation season was 1.9 times that at the beginning. Flood irrigation with freshwater after harvesting or before sowing flushes the accumulated salt out of root zone.

Climate

The experimental site is in a warm temperate zone with a continental desert climate, scarce precipitation and intense evapotranspiration (Fig. 12). Transpiration and evaporation through the roots, bare-soil strip and plant holes to the air is great, and the root-water uptake and the upper boundary of the soil evaporation depend on the dynamics of evapotranspiration.

Plant and plastic mulch

The roots distribution and density, which account for root-water uptake, vary with the growth stages, spacing between rows and in-row plants. The scope of the root-water uptake varies with the growth stages. Plastic film mulch changes the characteristics of the upper boundary of the SWFS. In addition, combinations of planting pattern and width of plastic mulch control the positions of left and right boundaries for the SWFS. The water content of the wide-rows zone was found to be higher than that of the narrow-rows zone and no-mulch strip at different growth stages (Fig. 13). The no-mulch strip had the lowest water content because of the soil evaporation and the long distance from the drip line. Although the narrow-rows zone was under the mulch and perpendicular to the drip line, the relatively lower water content was due to strong root-water uptake.

The soil temperature and water content are the main factors for controlling root growth. The water uptake and extent of wetting pockets can be significantly decreased by the soil evaporation (Communar and Friedman 2012). Comparing the mulch covering fractions (0, 30, 70 and 100 %), 70 % treatment was most beneficial for the utilization of soil water and seedling growth. The 30 % treatment made the roots grow deeper and no-mulch treatment accounted for the smallest root size (Zegada-Lizarazu and Berliner 2011). According to Tang et al. (2010), transpiration accounts for less than 70 % of the evapotranspiration for conventional furrow irrigation. However, in the work by Zhang et al. (2014), the fractions of transpiration to evapotranspiration before and after drip irrigation were 87.1 and 82.3 %, respectively, due to the plastic mulch above the drip line, strong root-water uptake, low water content of the bare soil strip and well-closed canopy at the flowering and bolling stages.

The aforementioned five controlling factors could change the SWFS through the effects on the potential sources and sinks, and the boundary conditions. Cognitions of these factors are guidelines for optimizing the SWFS. Rules of soil-water and salinity distribution may be obtained from the analysis of the SWFS patterns.

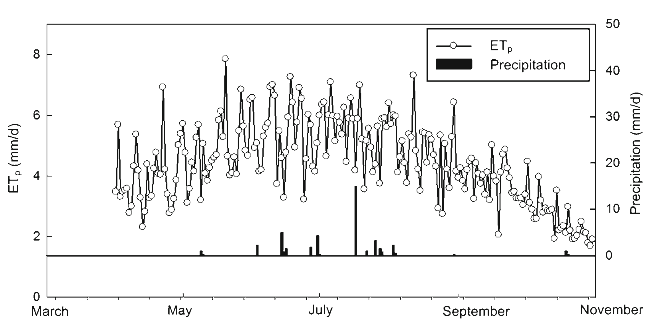

Fig. 12 Potential evapotranspiration (ET_p) and precipitation at the experimental site in 2012

Conclusions

Based on the distribution of the measured total soil-water potential, patterns of the soil-water flow system (SWFS) under mulched drip irrigation, from surface to the water table in a relatively homogeneous medium, were defined. The water-table fluctuation with irrigation events could be the sink or source of the SWFS. Root suction provided a strong sink. A divergent curved surface of zero flux (CSZF) resulted from irrigation events, i.e. water above the CSZF moved upward and water below the CSZF moved downward. The downward water flow below the

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CSZF before irrigation and the water-table fluctuation indicated that excessive irrigation occurred.

Distribution of water content and EC was controlled by the SWFS. The limited irrigation depth and evaporation of the bare soil resulted in the higher-salinity zones along the wetting front and near the bare soil strip. Soil hydraulic conductivity and storage, climate, irrigation, plant and the plastic film mulch were the main controlling factors of the SWFS. The factors could have effects on the potential sources and sinks, the boundary conditions and the size of the SWFS. The soil salinity increased drastically during the first irrigation month, from less than 5 to 10.1 mS/cm, and decreased slightly at the later stage. With the increase in applied water, the salt accumulation was restricted at the bolling stage. Irrigation with larger amounts of brackish water not only accumulated salts but also leached the salts to some extent. However, the salinity of the surface soil layer 0–60 cm at the end of the irrigation season was 1.9 times that at the beginning. Under the cover of plastic mulch, the water content of the wide-rows zone was higher than that of the narrow-rows zone due to the strong root-water uptake.

The optimum temporal and spatial management of the SWFS under drip irrigation with brackish water needs further investigation to increase water-use efficiency and avoid excessive irrigation. The precise observation of chemical and biological components of the SWFS is helpful for understanding the SWFS in the field.

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