Hydrogeol J (2015) 23:1719–1729
DOI 10.1007/s10040-015-1305-7

PAPER

Daytime and nighttime groundwater contributions to soils with different surface conditions

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Received: 28 March 2015 / Accepted: 31 July 2015 / Published online: 29 August 2015

Abstract Contributions of groundwater to the soil-water balance play an important role in areas with shallow water tables. The characteristics of daytime and nighttime water flux using non-weighing lysimeters were studied from June to September 2012 and 2013 in the extremely arid Xinjiang Uyghur Autonomous Region in northwestern China. The study consisted of nine treatments: three surface conditions, bare soil and cotton plants, each with water tables at depths of 1.0, 1.5, and 2.0 m; and plastic mulch with a water table at 1.5 m but with three percentages of open areas (POAs) in the plastic. The groundwater supply coefficient (SC) and the groundwater contribution (GC) generally varied with surface conditions. Both SC and GC decreased in the bare-soil and cotton treatments with increasing depth of the groundwater. Both SC and GC increased in the plastic-mulch treatment with increasing POA. Average nighttime GCs in the bare-soil treatments in July and August (the midsummer months) were 50.8–60.8 and 53.2–65.3 %, respectively, of the total daily contributions. Average nighttime GCs in the cotton treatments in July and August were 51.4–60.2 and 51.5–58.1 %, respectively, of the total daily contributions. The average GCs in June and September, however, were lower at night than during the daytime. Soil temperature may thus play a more important role than air temperature in the upflow of groundwater.

Keywords Arid region · Groundwater flow · Water supply · Diurnal variation · China

Electronic supplementary material The online version of this article (doi:10.1007/s10040-015-1305-7) contains supplementary material, which is available to authorized users.

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Introduction

The contribution of groundwater to the soil-water balance plays an important role in arid and semi-arid regions (Li and Wang 2014), such as the Xinjiang Uyghur Autonomous Region (hereafter Xinjiang) of northwestern China where rainfall is limited, potential evaporation is high, and the water table is shallow. Changes in the phreatic water in such regions are largely determined by the supply of water to the upper soil layers and little by percolation to lower layers. Cultivated soil in Xinjiang is saline, and the soluble salts in the groundwater or soil easily move upwards with water flow under strong evaporation, ultimately accumulating on the surface, and are likely to salinize the soil (Marlet et al. 2009). Salinity is a serious and chronic problem, significantly affecting agricultural productivity in arid and semi-arid regions (Liu et al. 2014; Malash et al. 2008); thus, a better understanding of the characteristics of groundwater contributions to soil in such regions is of vital importance.

Local evaporation potentials can cause water shortages and the accumulation of salts in the root zones, with negative effects on crop growth and agricultural production (Geerts et al. 2008; Qadir et al. 2007; Sharma and Minhas 2005). Accumulated salt on soil surfaces directly leads to secondary salinization of the soil, which negatively influences soil quality, compromises soil resources, and even threatens biodiversity (Dudley et al. 2008; Gowing et al. 2009; Han et al. 2011; Li et al. 2015). The effective management of such problems requires an understanding of the supply of groundwater to the soil for evaporation. Mulching with plastic film tends to conserve water, inhibit salinization, and improve the physical condition of the soil. Plastic-film mulching has, thus, become popular in arid Xinjiang (Zhang et al. 2014). Plastic mulch, however, requires holes for seeding and irrigation. Different crops require different planting densities, so the number of openings will also vary. Punched holes may have effects on the resistivity of the surface soil, and the movement of soil water may change when the total area of open holes increases or decreases. Different areas of plastic-mulch openings may thus differentially influence water flow. Different surface conditions such as bare soil, plastic mulch, or planted cotton, can also differentially influence the contribution of groundwater to the soil.

The effects of external environmental conditions such as temperature, relative humidity, wind speed, and solar radiation and of soil properties such as texture, porosity, structure, and water-table depth on characteristics of the upward flow of groundwater have been studied (Bezborodov et al. 2010; Yang and Yanful 2002). Many models of soil-water evaporation and transportation based on laboratory observation have also been developed (Bittelli et al. 2008; Jellali et al. 2009; Xu and Shao 2002; Zarei et al. 2010). Indoor simulations with ideal experimental conditions, though, often have limited practicability, but field experiments can be constrained by the limitations of acquiring detailed data, especially for the variations of groundwater flow.

Previous research, e.g. Xu et al. (2013) analyzed the relationship between the water table and the intensity of evaporation based on yearly data for water supply (yearly time scale). Shi et al. (2007) measured groundwater upflow under indoor simulated conditions of various soil structures and textures for 30 days (daily time scale) and also studied the evaporation of soil water with plastic mulch. Shi et al. (2007) then developed a model to estimate the rate of evaporation after evaluating the distribution of the soil water, but this model contained some limitations: (1) short experimental period, (2) pronounced differences between indoor and outdoor conditions, and (3) limited surface condition (only plastic mulch). Diaz et al. (2005) measured water contents over 31 days (daily time scale) in indoor soil profiles covered by tephra mulch of variable thickness and grain size. Xing et al. (2013) indicated that the accuracy of calculated groundwater contributions could be influenced by surface-water evaporation based on yearly data (yearly time scale). Daytime and nighttime contributions, however, have rarely been studied but are likely to identify key aspects of groundwater upflow.

Non-weighing lysimeters were used to collect the data for all treatments in this 2-year field experiment (Loos et al. 2007; Luo and Sophocleous 2010; Meissner et al. 2008; Unold and Fank 2008). Days were divided into daytime and nighttime to study in detail the variations in the diurnal supply of groundwater to the soil and to account for the differences between the daytime and nighttime contributions. The test involved three surface conditions, bare soil, plastic mulch, and planted cotton based on the field practices used by local farmers. The objectives of the study were (1) to identify the characteristics of the supply of groundwater to soils with different surface conditions, (2) to quantitatively analyze the groundwater contributions in the daytime and nighttime, (3) to evaluate the influence of the area of openings in the plastic mulch on groundwater upflow, and (4) to provide advice for planting cotton.

Materials and methods

Study area and lysimeters

The field experiment was conducted at the Bazhou Irrigation Experimental Station (41°36′ N, 86°12′ E, 950 m a.s.l.) in the town of Xinir in Korla, in the Xinjiang Uyghur Autonomous Region, northwestern China (Fig. 1). The study area has a typical temperate continental desert climate with mean annual temperature of 11.5 °C and a mean of 3,036 h of sunshine per year. The mean annual precipitation and potential evaporation are approximately 58.6 and 2788 mm, respectively. The depth of the water table ranges from 1.0 to 3.0 m and usually averages over multiple years at < 2.5 m in approximately half of the area. The depth of capillary water transport in this area is approximately 4.0 m.

The lysimeter system had been in operation since 2000 in the middle of a cotton field. The system consisted of soil cylinders, with heights of 1.0, 1.5, and 2.0 m and inner diameters of 0.7 m, and of rectangular soil containers, with lengths and widths of 1.5 and 1.0 m, respectively (Fig. 2). The entire system comprised these soil containers, a water supply, and monitoring equipment. The monitoring system was installed mainly in an underground compartment, and the surface of each soil container was flush with the ground surface. An air conditioner in the underground compartment maintained a constant temperature and pressure, so the effects of temperature and atmospheric pressure on the equipment could be eliminated. Each soil container sat on a 0.3-m base, containing a filter layer of gravel and sand. A graduated Mariotte bottle connected to the soil container maintained a constant water table and monitored the amount of water (groundwater) supplied to each container. The experimental soil was collected from a nearby field, air-dried, sieved through a 2-mm screen, and then compacted into the lysimeters. The experimental soil was silty loam with a distribution of particle sizes of 36.78 % 0.05–1 mm, 59.96 % 0.001–0.05 mm, and 2.62 % <

Fig. 1 Location of the experimental area *(Korla)* in the Xinjiang Uyghur Autonomous Region in northwestern China

0.001 mm. All containers were equally irrigated before the trial to ensure identical initial conditions.

Treatments and observations

The experimental treatments included three surface conditions, three depths of water tables, and three percentages of open areas (POAs) in the plastic mulch. These nine treatments each had three replicates (Table 1). The surface conditions were (I) bare soil, (II) cotton planted without plastic mulch, and (III) plastic-sheet mulch with different POAs but without cotton plants (Fig. 2). The depths of the water tables, based on the range of the local water tables, were set at 1.0, 1.5, and 2.0 m in I and II and at 1.5 m in III. The cotton plants in treatment category II were sown at 0.1-m intervals in two rows 0.35 m apart. For treatment category III, variable numbers of 9-cm^2 holes were cut evenly distributed on sheets of plastic mulch.

Salts can be exchanged between groundwater and underlying aquifers during groundwater recharge and discharge. The salts can also move upwards with upflow under evapotranspiration, resulting in salty groundwater and even the accumulation of salts in upper soil layers (Zammouri et al. 2007). Water from a local crop-land channel was, thus, used as the source of groundwater to lessen the effects of salt transfer to the surface. This water had total dissolved solids of 0.74 g L^{-1}, and so could be considered as freshwater.

Observations commenced in June and continued to early September in 2012 and 2013, coinciding with the high summer evaporative demands when rain is rare. Rectangular geothermometers were buried in the soil containers at depths of 5, 10, 15, and 20 cm to monitor soil temperature. Daily

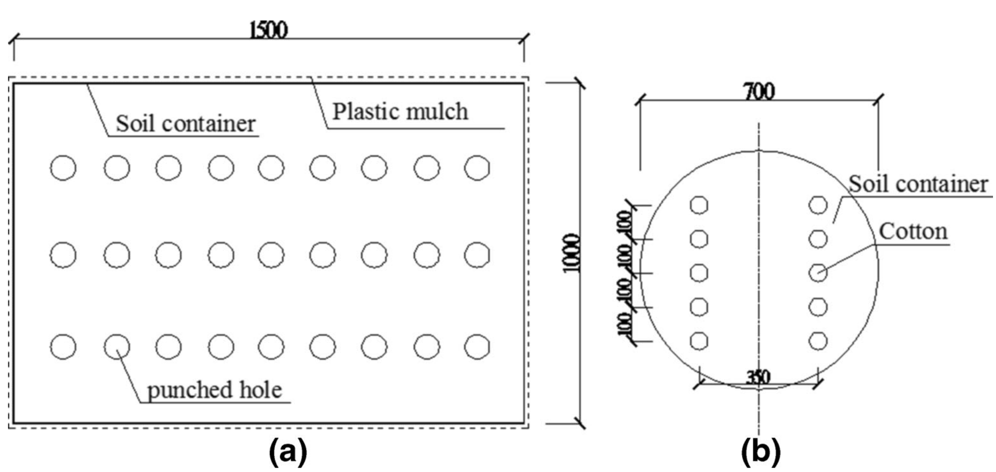

Fig. 2 Schematics of the surfaces of the soil containers in the non-weighing lysimeter systems for **a** treatment categories I and III, and **b** treatment category II. The units are mm

Table 1 Experimental treatments with different water-table depths and surfaces

Treatment category	Treatment	Water-table depth (m)	Surface	Notes
I	1	1.0	Bare soil	No mulch or cotton
	2	1.5		
	3	2.0		
II	4	1.0	Cotton plants	Planting is shown in Fig. 2
	5	1.5		
	6	2.0		
III	7	1.5	0.78 % POA[a]	Holes are shown in Fig. 2
	8	1.5	2.40 % POA	
	9	1.5	5.00 % POA	

[a] *POA* percentage of open area in plastic mulch (i.e. the ratio of the total area of the holes to the total surface area × 100)

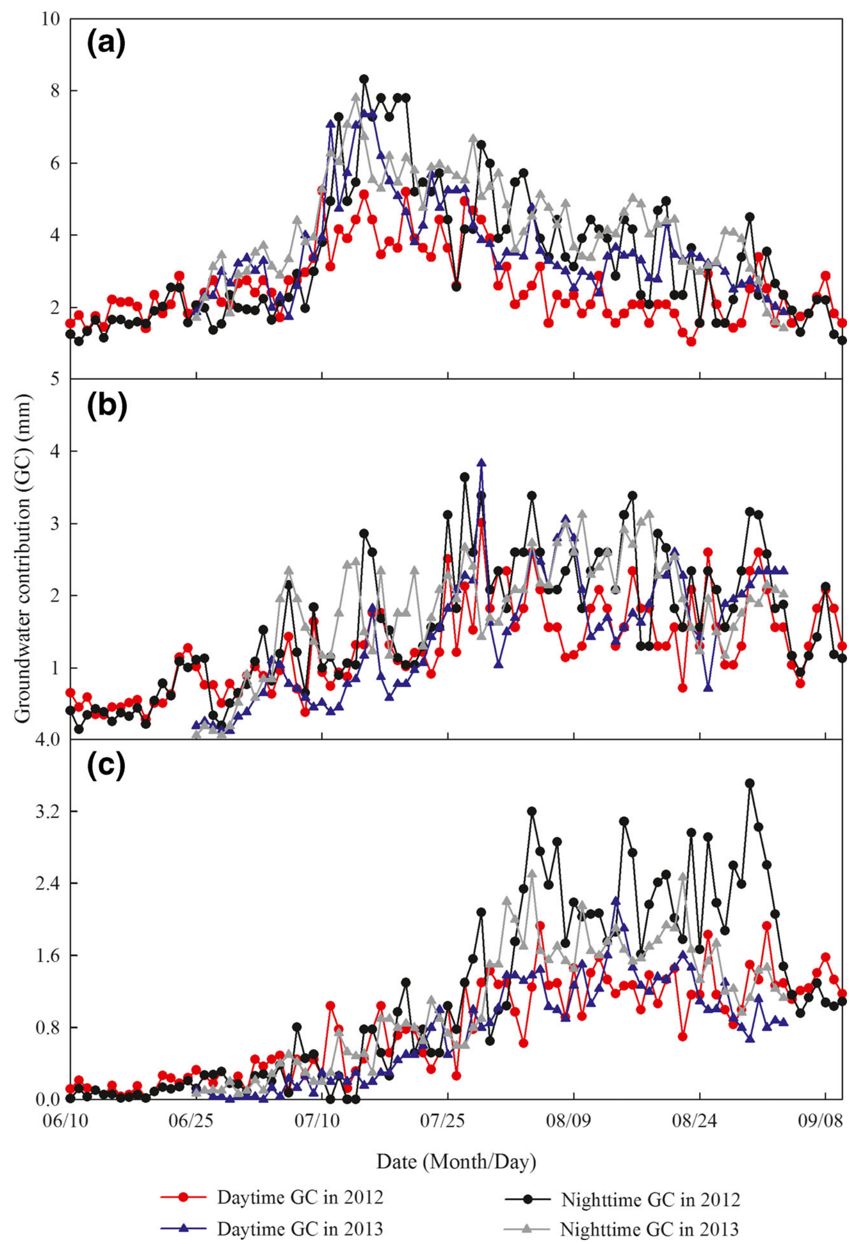

Fig. 3 Daytime and nighttime groundwater contribution for bare-soil treatments with water tables of **a** 1.0 m, **b** 1.5 m, and **c** 2.0 m, in 2012 and 2013. Raw data are presented in the electronic supplementary material (ESM)

water supply to the soil was calculated from the amount of water lost from the Mariotte bottle recorded at 08:00 and 20:00 each day. The amount of water lost to surface evaporation, representing the daily intensity of atmospheric evaporation, was measured by a volatilizer 20 mm in diameter using a weighing method. A supply coefficient (SC) was then calculated as the amount of the contribution of groundwater to the soil divided by the amount of surface-water evaporation within the same time period. Daytime and nighttime were defined as 08:00–20:00 and 20:00–08:00 (Beijing time), respectively. The observed data were analyzed using Microsoft Excel.

Results and analyses

Quantitative comparison of daytime and nighttime contributions

Groundwater contribution (GC) gradually decreased with increasing depth of the water table in both years (Fig. 3). The average nighttime GCs for July and August accounted for larger proportions of the total contributions. The average nighttime GCs in July and August 2012 were 56.5 and 62.7 % for the 1.0-m water table, 56.0 and 57.9 % for the 1.5-m water table, and 50.8 and 65.3 % for the 2.0-m water table, respectively (Table 2). The average nighttime GCs in July and August 2013 were 53.7 and 55.5 % for the 1.0-m water table, 59.7 and 53.2 % for the 1.5-m water table, and 60.8 and 56.8 % for the 2.0-m water table, respectively (Table 2).

The larger contribution of groundwater to the soil at night than during the daytime in July and August likely indicated that the daytime contributions could not meet the evaporative demands of the surface soil during this extremely arid period in Xinjiang. The water in surface layers was rapidly depleted, leading to disrupted capillary action, which in turn prevented the upward flow of groundwater and vaporization. The weather in June and September, however, was warm but not hot, and the water lost by evaporation was compensated by a continuous supply of water from functional capillary action, which led to a larger supply in the daytime than at night.

GCs for the cotton treatment with a water table of 1.0 m peaked in early August in both years (Fig. 4), because the cotton grew exuberantly at this time and required the largest amount of water uptake by the roots. The roots were of such sufficient length during the growing period that they never failed to absorb enough water from the groundwater. GCs tended to increase gradually in the treatment with a water table of 1.5 m and to increase sharply with a water table of 2.0 m, suggesting that the 1.5-m depth is common in cotton crops (Bu et al. 2013) but that roots at first failed to reach the deeper groundwater but eventually grew enough. The GC sharply increased near the end of July/early August in both years along with continuous upward fluxes to the soil to satisfy the water requirements of the crop. The average nighttime GCs in July and August for all three depths of water table accounted for the largest proportions of the total contributions. The average nighttime GCs in July and August 2012 were 54.1 and 53.5 % for the 1.0-m water table, 60.2 and 53.5 % for the 1.5-m water table, and 59.5 and 58.1 % for the 2.0-m water table (Table 2), respectively. The average nighttime GCs in July and August 2013 were 56.5 and 51.5 % for the 1.0-m water table, 51.8 and 54.3 % for the 1.5-m water table, and 51.4 and 55.1 % for the 2.0-m water table, respectively (Table 2).

Nighttime GC in the cotton treatments was thus larger than daytime GC in July and August, but smaller in June and September (Figs. 3 and 4). The average GC was also larger than that in the bare-soil treatments, largely due to the water uptake by roots driven by evapotranspiration. The difference in GC between the bare-soil and cotton treatments was significant. This difference was small early in the growing season but

Table 2 Average daytime and nighttime groundwater contributions (mm) and surface-water evaporation (SWE) in the nine treatments from June to September 2012 and 2013

Treatment		2012				2013[b]	
		June	July	August	September	July	August
1	Daytime	2.04	3.63	2.08	2.03	4.50	3.21
	Nighttime	1.73	4.71	3.50	2.01	5.21	4.00
2	Daytime	0.63	1.31	1.69	1.54	1.14	1.97
	Nighttime	0.54	1.67	2.32	1.53	1.69	2.24
3	Daytime	0.17	0.61	1.22	1.39	0.40	1.28
	Nighttime	0.12	0.63	2.30	1.35	0.62	1.68
4	Daytime	3.81	6.15	7.09	3.81	5.16	8.28
	Nighttime	3.29	7.24	8.14	3.64	6.70	8.78
5	Daytime	1.20	2.14	4.46	3.40	2.53	4.85
	Nighttime	0.89	3.23	5.13	2.97	2.72	5.76
6	Daytime	0.36	1.02	3.31	2.32	1.01	2.65
	Nighttime	0.28	1.50	4.58	2.30	1.07	3.25
7	Daytime	—[a]	0.63	0.45	—	0.59	0.51
	Nighttime	—	0.72	0.50	—	0.71	0.68
8	Daytime	—	0.80	0.48	—	0.70	0.58
	Nighttime	—	0.92	0.73	—	0.82	0.75
9	Daytime	—	0.95	0.69	—	0.84	0.62
	Nighttime	—	1.21	1.10	—	1.01	1.14
SWE	Daytime	7.06	7.26	6.71	6.27	7.18	6.54
	Nighttime	2.59	2.12	1.80	1.79	2.07	1.95

[a] — indicates no data

[b] The average groundwater contributions for June and September 2013 are omitted due to the short times in these 2 months, only 6 and 3 days, respectively (the verification experiment was conducted from 25 June to 3 September 2013)

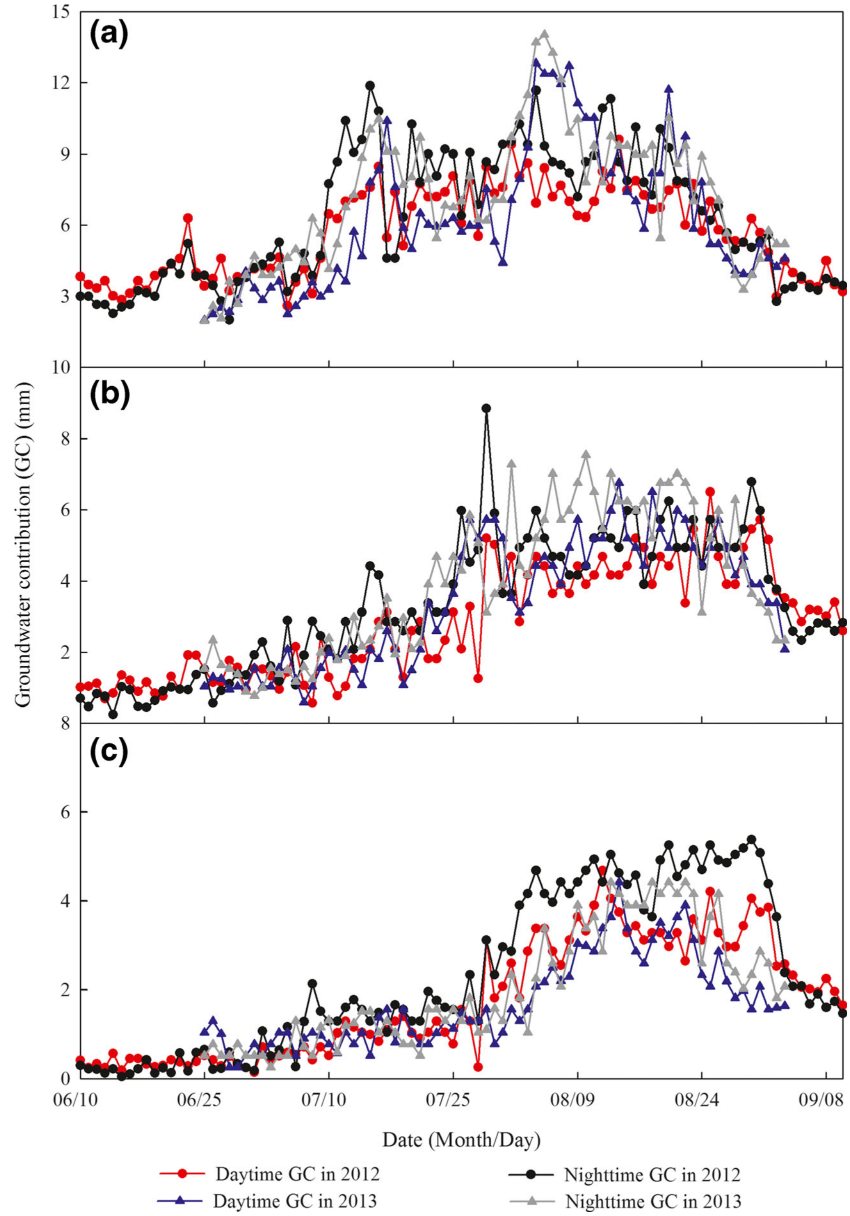

Fig. 4 Daytime and nighttime groundwater contribution for cotton treatments with water tables of **a** 1.0 m, **b** 1.5 m, and **c** 2.0 m, in 2012 and 2013. Raw data are presented in the ESM

became larger during the flowering and boll-opening stages, largely due to the larger water requirements in these stages in contrast to seedling and budding stages and to the longer roots in the latter stages. The difference in GC between these treatments gradually decreased with increasing depth of the water table.

The average daytime and nighttime GCs for June, July, August, and September throughout the 2 year period are listed in Table 2. The variations of water supply with depth of water table and with land-cover type were typical (Lautz 2008; Mastrocicco et al. 2010; Qiu et al. 2014; Talebnejad and Sepaskhah 2015), but the average GCs in June and September 2012 were larger in the daytime than the nighttime, and the average GCs in July and August were smaller in the daytime than the nighttime. Consequently, the experiments for July and August in 2013 were conducted, which confirmed the 2012 observations (Table 2).

These results suggest that the average GCs in June and September in Xinjiang are larger in the daytime than at night but are larger at night in July and August. In other words, average nighttime GCs account for higher proportions of total contributions during the hottest weather.

Daytime variations of the groundwater supply coefficient (SC)

Similar changes were observed for SC in both years at the three depths of water tables in the bare-soil and cotton treatments. Contributions were smaller for the bare-soil treatments due to the uptake of water by the roots of the cotton plants. As expected, the SCs were lowest for the plastic-mulch treatments, with values increasing with the POAs (Fig. 5). The SCs of the bare-soil and cotton treatments decreased with increasing depth of water table over the experimental period. The average SCs of the bare-soil and cotton treatments were 0.40 and 0.85 for the 1.0-m water table, 0.2 and 0.44 for the 1.5-m water table, and 0.12 and 0.28 for the 2.0-m water table, respectively.

The SC for the 1.0-m water table first increased, peaking in late July/early August, and then decreased. This pattern suggested that the flux mechanisms became fully developed for this water table but not for the 1.5- and 2.0-m water tables. The average SCs for the bare-soil treatments in June, July, and August were 0.26, 0.52, and 0.39 for the 1.0-m water table; 0.08, 0.19, and 0.27 for the 1.5-m water table; and 0.03, 0.09, and 0.19 for the 2.0-m water table, respectively (Fig. 5). The SC patterns were similar for the plastic-mulch treatments. The average SCs for cotton treatments in June, July, and August, however, were 0.52, 0.90, and 1.11 for the 1.0-m water table; 0.20, 0.31, and 0.70 for the 1.5-m water table; and 0.07, 0.14, and 0.52 for the 2.0-m water table, respectively.

Nighttime variations of the groundwater supply coefficient (SC)

Supply coefficients (SCs) in the nine treatments were much lower in the daytime (Fig. 5) than the nighttime (Fig. 6). SCs were higher in July and August than in June and September.

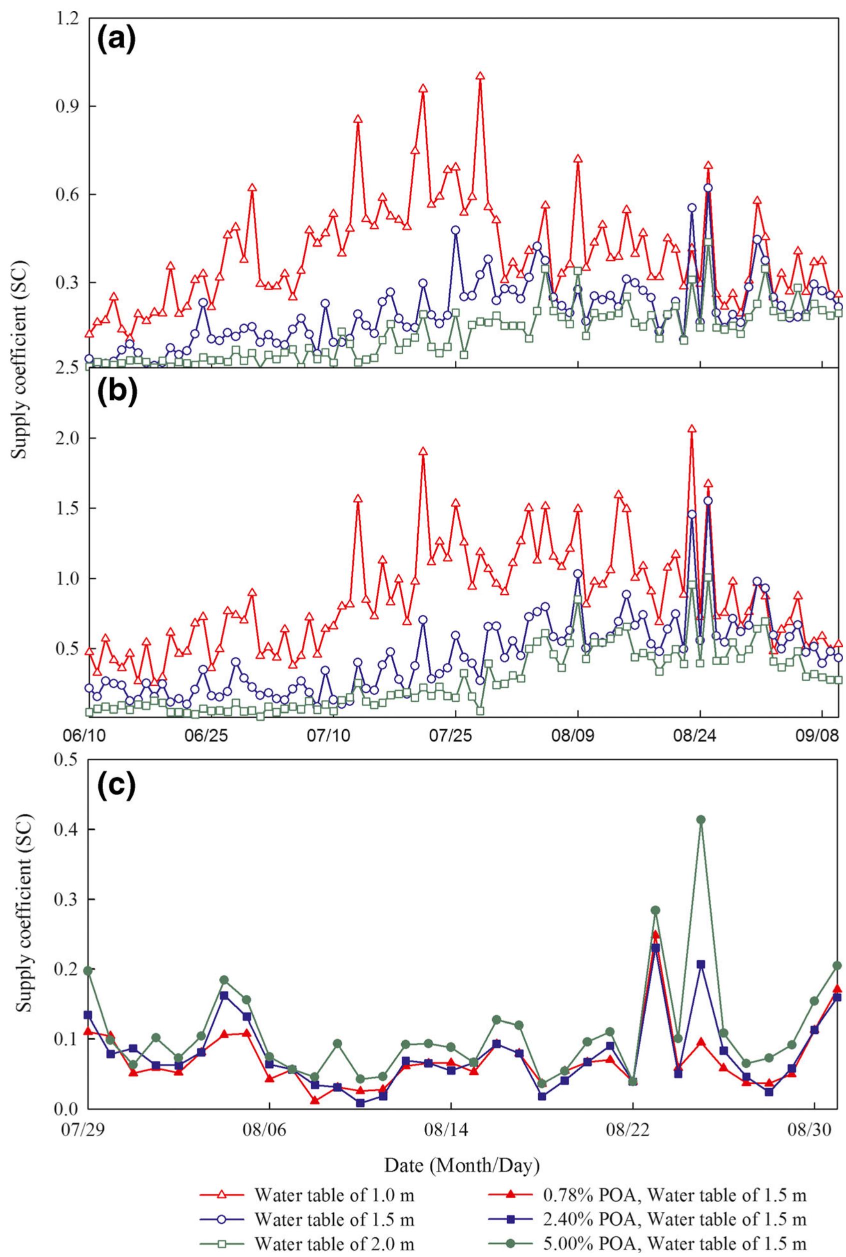

Fig. 5 Dynamic variations of daytime supply coefficients for the **a** bare-soil, **b** cotton, and **c** mulch treatments in 2012. *POA* percentage of open area in the plastic mulch; raw data are presented in the ESM

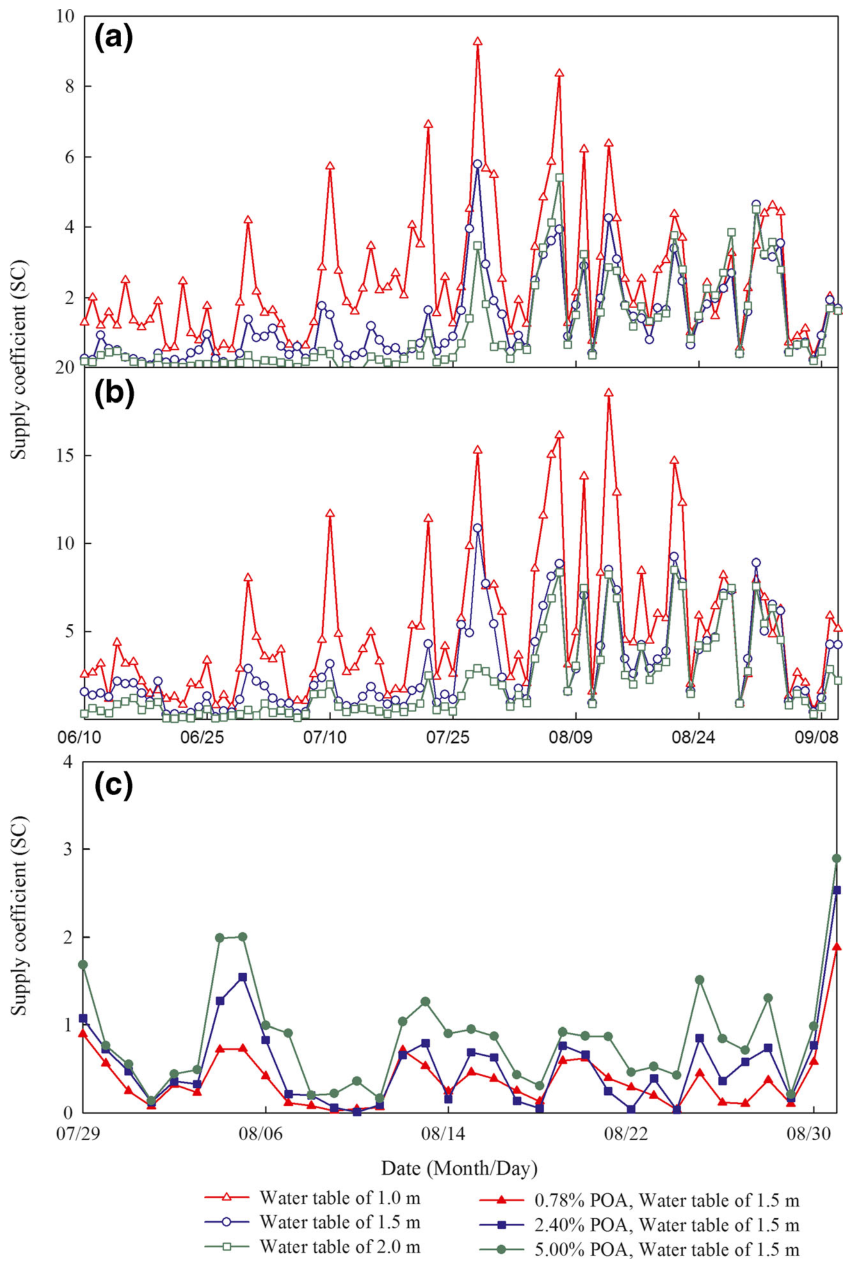

Fig. 6 Dynamic variations of nighttime supply coefficients for the **a** bare-soil, **b** cotton, and **c** mulch treatments in 2012. *POA* percentage of open area in the plastic mulch; raw data are presented in the ESM

The average SCs for bare-soil treatments in June, July, and August were 1.44, 2.88, and 2.94 for the 1.0-m water table; 0.39, 1.17, and 2.02 for the 1.5-m water table; and 0.17, 0.47, and 1.89 for the 2.0-m water table, respectively. The average SCs for the cotton treatments in June, July, and August were 2.37, 4.78, and 7.40 for the 1.0-m water table; 1.17, 2.33, and 4.64 for the 1.5-m water table; and 0.45, 1.01, and 4.24 for the 2.0-m water table, respectively. SC fluctuated more at night than in the daytime, indicating that the upflow of groundwater was more sensitive to the meteorological conditions at night. Relatively stable meteorological conditions in the daytime such as temperature, atmospheric pressure, and humidity, may foster a stable water supply, while irregular changes of air temperature and humidity at night may foster an unstable water supply. Low nighttime air temperatures had little effect on groundwater upflow, but the lower nighttime soil temperatures foster larger supplies at night than in the daytime.

Soil temperatures in the shallow layers (≤20 cm) generally increased from 08:00 to 20:00 and were always higher than the air temperatures (Fig. 7). Mean topsoil (5 cm) temperature was near 40 °C, especially at midday, which decreased soil-water content and led to disrupted capillary action (i.e. decreased GCs). Soil temperature, however, obviously decreased from 20:00 to

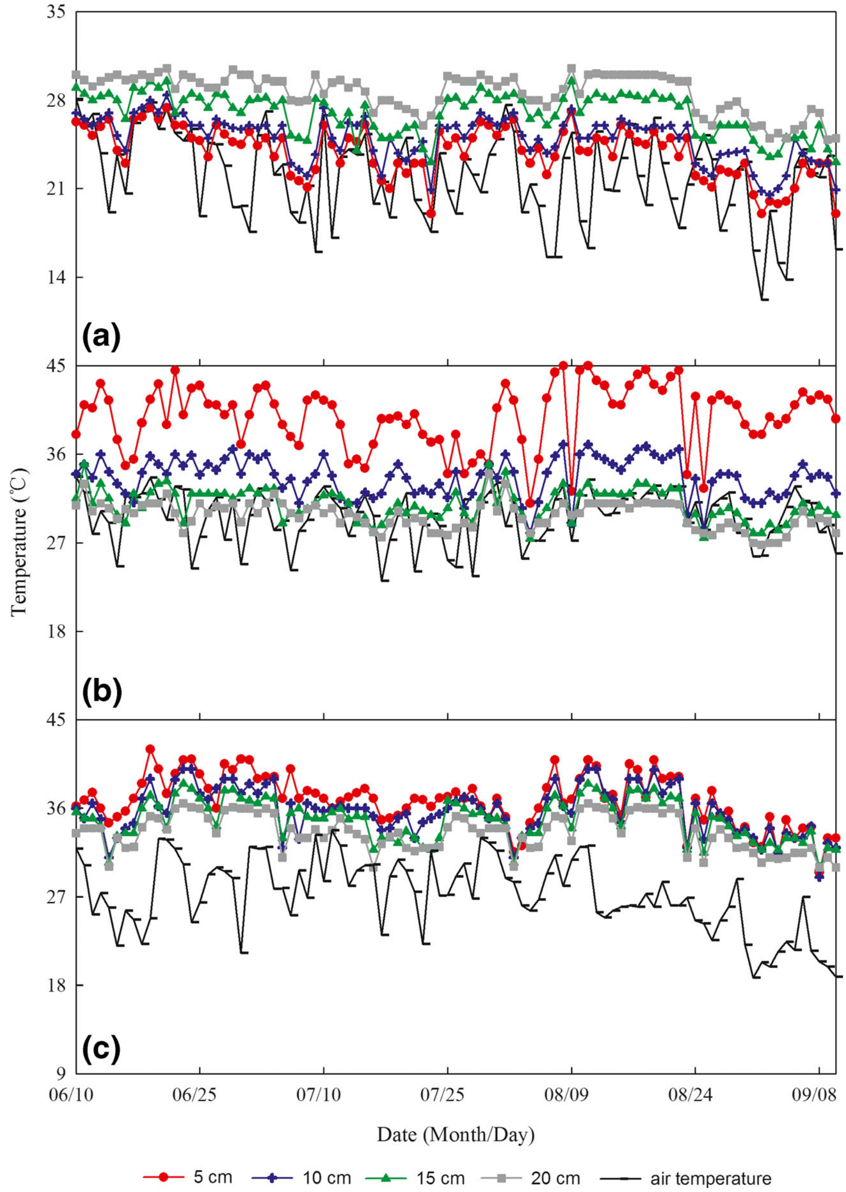

Fig. 7 Variation of soil temperature in the 5, 10, 15, and 20 cm layers at times **a** 08:00, **b** 14:00, and **c** 20:00 during the 2012 period; raw data are presented in the ESM

08:00, during which time GC increased. The extent of variation of temperature during the day was generally larger in the topsoil than the air, and this variation of soil temperature likely produced the changes in GC. The intensity of the groundwater supply in summer (i.e. July and August) was, thus, likely determined largely by the changes of soil temperature resulting from the changes of air temperature but not directly by air temperature.

Discussion

Amount of groundwater contribution to the soil

This 2-year experiment showed that the amount of water supplied to the soil from groundwater in July and August was larger at night than in daytime, which deviated from the conventional understanding that higher daytime temperatures would increase the supply. The results in this study are consistent with those by Xia et al. (1995) and Li et al. (2012), who tested only bare soil. And this study further supported the characteristic of a diurnal water supply to the soil in the plastic-mulch and cotton treatments.

The results may be due to one or more of three mechanisms. Firstly, to some extent, there is a delay between water supply and atmospheric evaporative demand. Secondly, as solar radiation increases after midday, the water-carrying capacity of the soil decreases due to the lower soil-water content in the surface layers. The evaporative surface where soil moisture is vaporized to the air may become slightly deeper due to the disrupted capillary action in the upper soil layer. This deeper evaporative surface would lead to less evaporation of groundwater (Ma and Li 2011). As solar radiation decreases near 18:00, the water-carrying capacity of the soil exceeds the atmospheric evaporative demand, which would increase the soil-water content in the surface layers. The evaporative surface, however, would return closer to the soil surface when the disrupted capillary action recovered (Li et al. 2014). Thirdly, the surface tension at the interface of the soil water and the atmosphere increases at night under the influence of the lower temperatures of the surface soil, so the soil-water suction increases and the soil-water potential decreases. This mechanism may lead to the flow of soil water from low-suction sites to high-suction sites, namely, from warm to cold sites (i.e. from underground to the surface). These mechanisms suggest that groundwater flows upwards not only in the daytime with high temperatures, but also at night, which was even stronger in this experiment. The results could, thus, benefit the design of a reasonable scheduling of irrigation.

Optimum percentage of open area (POA) of plastic mulch

The supply of groundwater in the plastic-mulch treatments tended to increase as POA increased, because POAs naturally increase evaporation, leading to different groundwater contributions to the soil. GCs, however, may not increase linearly with POA. As Shi et al. (2013) and Xing et al. (2014) pointed out, GC in saline soils first increased to a peak as POA increased but decrease thereafter as POA continued to increase. The soluble salts in soil or groundwater may be transported by upward water flow and accumulate on the soil surface forming salt crusts around the holes in the mulch, which in turn could directly inhibit upward flow, thereby resulting in reduced GC (Ghamarnia and Jalili 2014; Grünberger et al. 2008; Xing et al. 2014). The POA where GC peaks could be referred to as the optimum opening ratio of the plastic-sheet mulch. Determining the optimum opening ratio would benefit the planting of crops and the characteristics of soil-water/salt transport. Further studies, however, are needed on the influence of salt crusts on the evaporation of soil water, and for determining the optimum opening ratios for different crops. The findings of the present study, though, should help the design of reasonable irrigation strategies for minimizing salt leaching in cropland.

Conclusions

Groundwater is an important water resource, and upflow plays an important role in crop growth in regions with shallow groundwater where it is viewed as a potential source of water for crops. The results of this 2-year field experiment demonstrated that soil-surface conditions strongly influenced GC. SC was highest in the cotton treatments, followed by the bare-soil and plastic-mulch treatments. Both GC and SC tended to decrease with increasing depth of water table in the bare-soil and cotton treatments. Both GC and SC gradually increased with POA in the plastic-mulch treatments due to the increasing intensity of atmospheric evaporation. Daytime and nighttime GCs first increased and then decreased from June to September. Nighttime SCs fluctuated more than daytime SC due to the less stable meteorological conditions at night.

Average GCs in June and September were smaller at night than in the daytime, which was expected. Average GCs in July and August, however, were larger at night than that in the daytime, which was unexpected. These results suggest that groundwater flows upwards primarily in the daytime in June or earlier and in September or later but primarily at night in July and August, the hottest time of the summer.

Acknowledgements We greatly appreciate the first review from Dr. Martin Parkes. This work was financially supported by the National Sci-Technology Supporting Program for "Twelfth Five" Plan of China (grant No. 2012BAD08B01), the Special Scientific Research Fund of Public Welfare Profession of MWR, China (grant No. 201301016), and the National Natural Science Foundation of China (grant Nos. 51379173, 51279167).

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