The impact of plant water uptake and recharge on groundwater level at a site in the Loess Plateau of China

H. Yasuda, R. Berndtsson, O. Hinokidani, J. Huang, T. Saito, J. Zheng and R. Kimura

ABSTRACT

Shallow groundwater in unconsolidated sediments represents a substantial water resource in the Chinese Loess Plateau. However, prior to development of the water supply for agriculture, annual and seasonal fluctuation of the recharge mechanism should be clarified. Since the region is arid, the effect of plant water uptake on groundwater fluctuation must also be assessed. A study was therefore undertaken to clarify groundwater recharge together with interaction between the plant ecosystem and shallow groundwater at a field site in the Loess Plateau of China. Observations showed that recharge response of the groundwater level (GWL) was limited except for intensive rainfall during the rainy season. The main recharge to the groundwater occurred from horizontal inflow from focused recharge at the upstream end of the site. Fluctuation of the GWL produced by plant water uptake was monitored during the growing season. For seasonal fluctuation of GWL, temperature was most important, while for diurnal fluctuation of GWL during the growing season, solar radiation was most important. During the growing season, the GWL declined during the daylight hours and recovered during the night. The diurnal fluctuation was well synchronized with the solar radiation, consistent with plant-water uptake by shrubs surrounding one of the observation wells.

Key words | arid region, Chinese Loess Plateau, dam farmland, groundwater, plant water uptake

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INTRODUCTION

The Chinese Loess Plateau covers an area of some 640,000 km^2 in the upper and middle reaches of the Yellow River and forms a climatic transition zone from semiarid to hyper-arid areas (e.g., Wang *et al.* 2011). The desertification front has continuously advanced into the Loess Plateau during the last two millennia. The Loess Plateau is an important source of water and sediments for the Yellow River and the origin of the river name is the yellow colored sediment (loess) of the Loess Plateau. About 1.5 billion tons of sediment flows into the Yellow River every year (Wang & Jiao 1996). In order to reduce erosion, an extensive system of check-dams has been built. Many of these dams were completely filled up by sediments within a few decades after their construction. However, the sediment filled dams have now turned into level and highly fertile farmlands. By the beginning of the 21st century, about 113,500 check-dams were built, creating 3,200 km^2 of farmlands with high productivity, and intercepting a total of 700 million m^3 of sediments that otherwise would have poured into the Yellow River (Xu *et al.* 2004). Flat and fertile dam farmland has high potential of agricultural development. On the other hand, the arid climate and the lack of water supply often hamper development of the dam farmland. Most of the Loess Plateau receives an annual precipitation of 100–500 mm only. Thus, existing water resources are vulnerable to overexploitation (e.g., Yasuda *et al.* 2009). Owing to the

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limited annual precipitation, groundwater is often the only source of freshwater during the dry period.

Shallow groundwater is common in the sediment-filled check dams. For agricultural utilization of the dam farmland, groundwater responses, such as annual and diurnal fluctuations, and recharge mechanisms need to be better understood. Rainfall over the dam farmland and inflow from upstream areas could be a potential recharge source to the shallow groundwater. Research has shown that plant water uptake may have large influence on water table fluctuation in areas with shallow groundwater. White (1932) reported one of the earliest contributions of plant water uptake effects on diurnal fluctuation of the water table. Todd & Mays (2005) showed that diurnal groundwater fluctuation was corresponding to evaporation and transpiration losses. Steinwand *et al.* (2006) reported that plant water uptake accounted for 60–81% of the evapotranspiration. Butler *et al.* (2007) showed that wells in riparian zones displayed a diurnal groundwater fluctuation due to plant water uptake. Engel *et al.* (2005) observed sap flow of eucalyptus and groundwater level in the Pampas grassland and reported that transpiration rate was 2.0–3.7 mm/day. Nippert *et al.* (2010) showed that diurnal water table fluctuations were due to vegetation water consumption and that the magnitude of diurnal fluctuation was stronger in shallow wells. Asbjornsen *et al.* (2007) observed that transpiration-influenced water table depth in woodland areas was three times that of savanna areas. The tendency of the groundwater level to decline due to plant water uptake during the growing season has been reported for different arid locations such as Argentine Pampa (Jobbágy & Jackson 2004; Engel *et al.* 2005), New Mexico (Cleverly *et al.* 2006), and Kazakhstan (Ostrovsky 2007). In the semiarid Inner Mongolia (200 km west of the study area of the present study), Ohte *et al.* (2003) reported that shrub (*Salix matsudana*) water uptake caused the groundwater to decline from spring to summer.

In view of the above studies, it is clear that depending on type and density, vegetation may have large impact on groundwater level fluctuation. This might be especially important in vegetated areas with shallow groundwater, such as in the Chinese Loess Plateau. Accordingly, the objective of this study was to clarify recharge mechanisms to a shallow groundwater aquifer and the interaction between groundwater and the plant ecosystem at a field site in the Chinese Loess Plateau. This was done by observing rainfall, runoff, and groundwater levels (GWLs) in a small sediment-filled check dam together with climatic variables such as temperature and solar radiation.

STUDY AREA

The study area was a dam farmland (sediment-filled check dam) in Liudaogo basin in Shanxi Province, China (Figure 1). The annual precipitation is 400–500 mm. The rainy season usually starts in June and ends in September. July and August are the two wettest months with on average 115 and 120 mm/month, respectively (Figure 2; Huang *et al.* 2008; Yasuda *et al.* 2009). The check dam was constructed in the 1970′s and the reservoir of the dam was completely filled with sediments after about three decades. Sediments were accumulated over the original valley surface (sandstone) and a groundwater table has developed in the infilled sediments. The upper part of the sandstone is strongly weathered. During recent years, level farmland was created on top of the sedimentary fill (Figure 3(a), Figure 4).

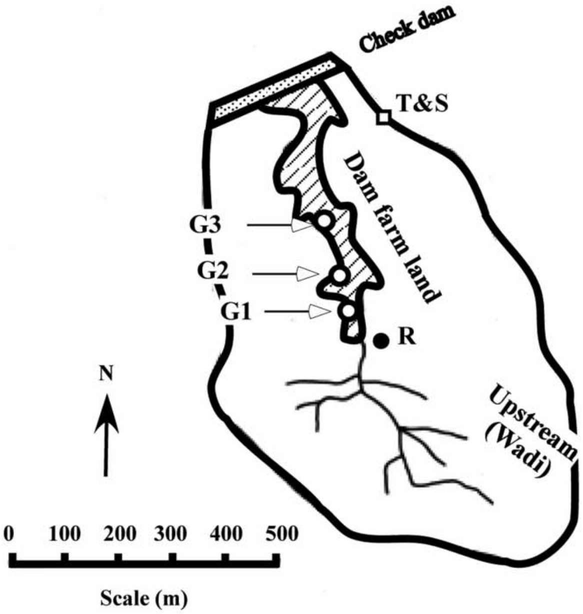

Figure 1 | Servation arrangement. G1–G3: observation wells; R: rainfall gauge; T&S: temperature and solar radiation sensors.

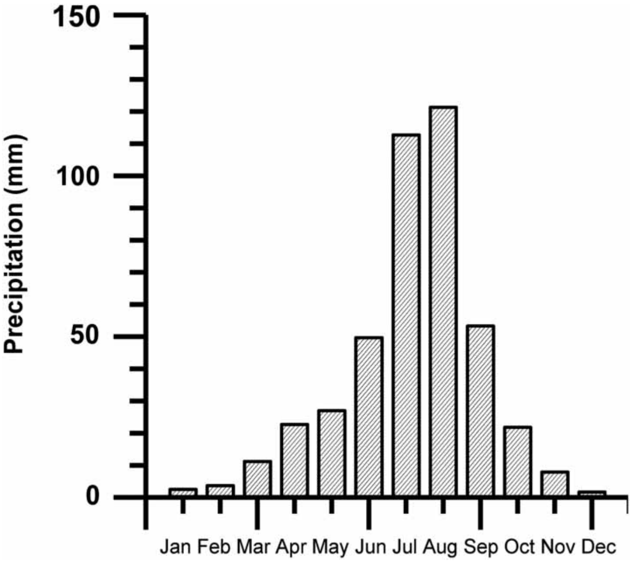

Figure 2 | Monthly rainfall.

The physical properties of sediments in the study area were reported by Zheng (2004). These correspond to clay and silty soil and the capillary rise is less than about 0.5 m. The hydraulic conductivity is 2.9×10^{-4} cm s^{-1}. Corn was planted at the downstream-end, but most of the area is not used for farming except for rarely cattle feed collecting. Thus, most of the dam farmland is covered by grass and interspersed shrubs. Smaller trees and shrubs grow at the upstream of the study area. Groundwater is not currently used in the experimental area. Consequently, there are no wells except for the observation wells used in this study.

Groundwater level recorders, HM-910-02-30 (*Sensez*), were used for water table observations in three wells (G1–G3; Figure 1, Figure 4). The location of these observation wells in relation to topography is shown in Figure 5(a). The specification such as depth from the ground surface, position of screen and groundwater depth is shown in Figure 5(b). The observation wells were dug by hand augers and the screen was set at 1.5 m height from the well bottom. Observation well G1 was located near the top boundary of the dam farmland (Figure 4) and it was surrounded by shrubs (*Salix matsudana*). Rainfall (R; RGB M002, *On set*), was measured in the upstream hilly region and temperature (T; HMP45A, *Vaisala*), and solar radiation (S; CNR-1, *Kipp & Zonen*) were observed at the downstream basin boundary (Figure 1).

Gully stream runoff from the upstream hilly area was observed after high intensity rainfall events several times a year (Hinokidani *et al.* 2006; Huang *et al.* 2008). The upstream hilly area is partly covered by short grass. In general, the Loess Plateau is well known for serious erosion and steep slopes in the only partially vegetated upstream hilly region. Runoff water in the stream finally flowed into the dam farmland as small flash floods (Figure 3(b)). Huang *et al.* (2008) and Hinokidani *et al.* (2010) reported characteristics of the surface flow in the upstream hilly

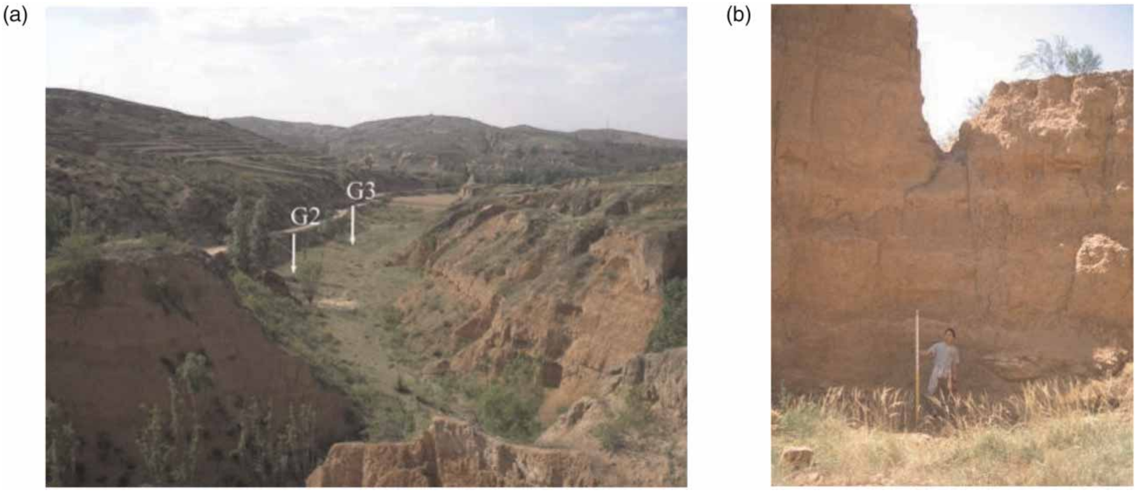

Figure 3 | (a) The study area (dam farmland). A view from the upstream hill. The reservoir has been filled by sediments. (b) Top boundary of the dam farmland. Ephemeral runoff from the upstream hilly region flows into the farmland through a waterfall. The rod length is 2 m.

Figure 4 | The observation wells. G1 is surrounded by shrubs (*Salix Matsudana*). G2 and G3 are surrounded by short grass. The photos of G2 and G3 are taken from downstream of the wells.

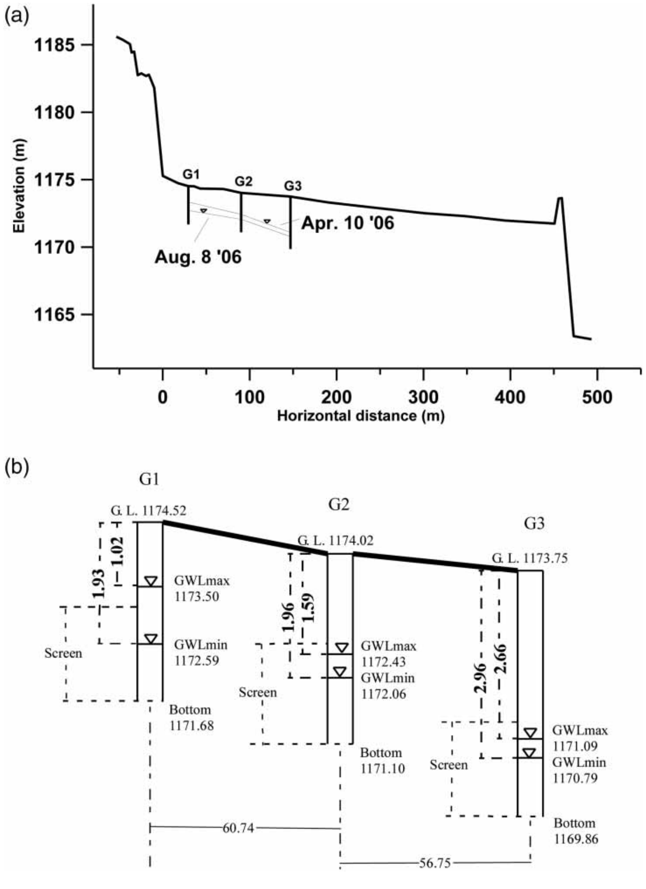

Figure 5 | (a) Location of the observation wells on the cross-section of the dam farmland. (b) Specification of the wells (m). The length of screen is 1.5 m.

area. Runoff occurrence in the gully of the upstream hilly area can be classified according to two conditions:

1. when rainfall duration is several hours (but less than 10 h), surface runoff is generated for a rainfall intensity of at least 3 mm/5 min, and
2. when the rainfall duration is more than 10 h, surface runoff is generated for a rainfall intensity of at least 0.6 mm/5 min.

OBSERVATION RESULTS AND DISCUSSION

Seasonal fluctuation

Figure 6 shows groundwater level at the three observation wells (G1–G3) with precipitation, solar radiation, and daily maximum and minimum temperature of the dam farmland from November 2004 to November 2006. The GWL at G2 was not observed from May to November 2005 and after September 2006. The GWL observation at G3 started in November 2005 and was not observed after August 2006. The solar radiation and maximum and minimum temperature are given as 31-day moving averages. It is evident from Figure 6 that there is a depression in GWLs during the growing season. There is also a clear response to precipitation at G1. During the growing season, the GWL was lowered as the plant water uptake was large, as grass and shrubs contribute to plant water uptake. However, during the same period, summer rainfall recharges the groundwater. According to Figure 6, evapotranspiration exceeded recharge by rainfall during the summer period causing the water table to decline.

The GWL started to decline in April to May. The GWL was at minimum level from June to August and it started to recover from September. At G1, groundwater depth (GWD) was smallest (1.02 m; GWL 1173.50 m) on

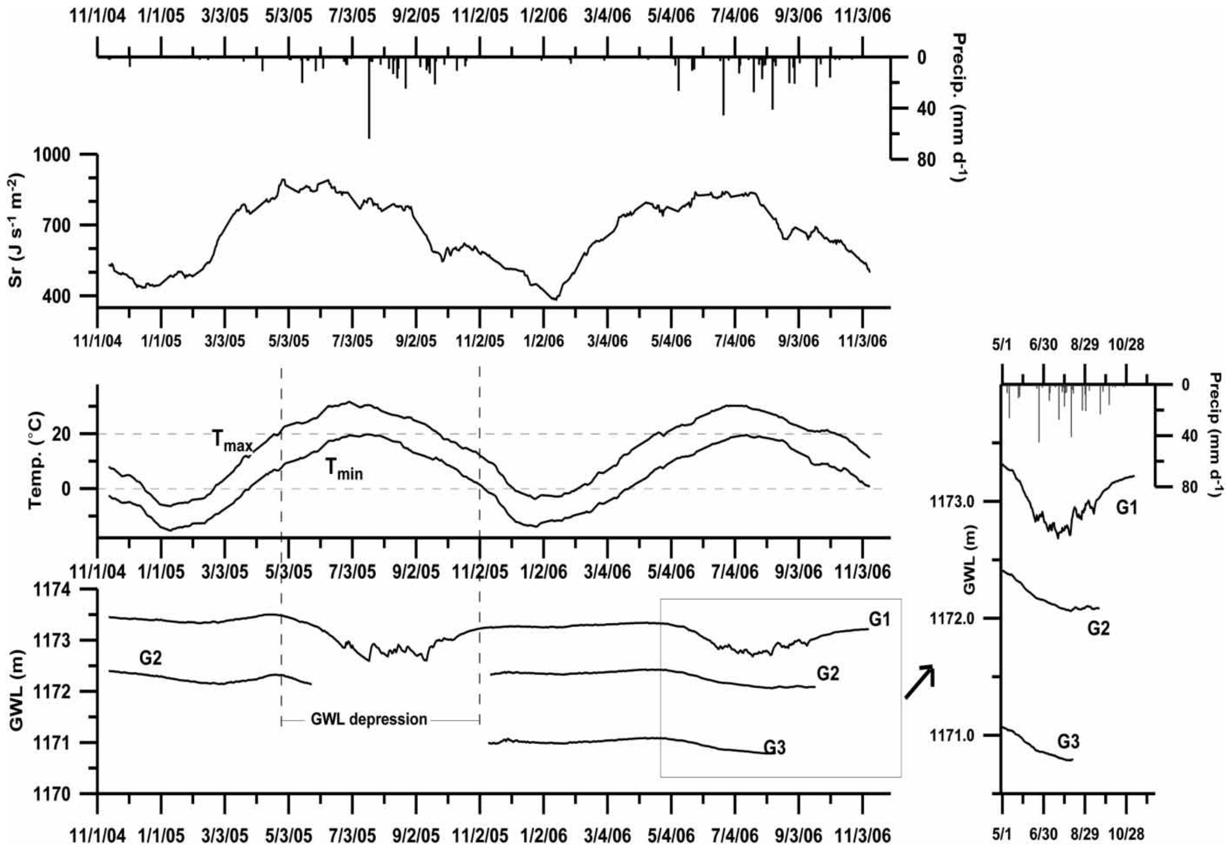

Figure 6 | Precipitation, daily maximum solar radiation (Sr), maximum–minimum temperature (T_{max}, T_{min}) and daily groundwater level (GWL). Solar radiation and temperature are given as 31 days moving average of daily data. The right side is response of GWL (G1–G3) to precipitation during summer 2006. The vertical axis (GWL) is expanded. No data for GWL at G2 from May to November 2005.

April 15th in 2005, and it was largest (1.93 m; GWL 1172.59 m) on July 19th in 2005, and the difference was 0.91 m. For G2, GWD was smallest (1.59; GWL 1172.43 m) on April 27th in 2006 and it was largest (1.96 m; GWL 1172.06 m) on August 8th in 2006, with a difference of 0.37 m. The GWD of G3 was smallest (2.66 m; GWL 1171.09 m) on April 24th in 2006 and it became the largest (2.96 m; GWL 1170.79 m) on August 2nd in 2006, with a difference of 0.30 m. Low GWLs occurred from May to September when the maximum temperature exceeded approximately 20 °C both in 2005 and 2006. From the figure it is also clear that there is an apparent relationship between the GWL and temperature and solar radiation. Since water uptake by plants due to transpiration caused a GWL depression, there is also a strong correlation between temperature and solar radiation and GWL.

Recharge to groundwater

The response of the GWL to rainfall was pronounced only at G1 but not at G2 and G3. The response of the GWL to rainfall was only pronounced during the growing season. Such a prompt recharge corresponding to intensive rainfall was caused mainly by inflow of water from the upstream hilly area to the dam farmland (Huang *et al.* 2008). In the case of intensive rainfall, runoff occurred at the gully stream in the upstream hilly area and flowed into the dam farmland (Figure 3(b)). The right-hand side of Figure 6 shows a vertical enlargement of daily rainfall and GWL of G1, G2, and G3 during the summer of 2006. The response of the GWL to rainfall at G1 is clear. However, the response at G2 was muted and only observed during the low GWL condition in August and September. Unfortunately, the recording length of G3 was limited, and there was almost no response to rainfall during this period.

Figure 3(b) shows the location of a waterfall at the top boundary of the dam farmland. For intensive rainfall, ephemeral runoff was occasionally generated during the observation period and runoff water discharged through the waterfall down to the dam farmland. The groundwater in the dam farmland was recharged by runoff water from the upstream hilly area. The top boundary was thus the recharge location. And the runoff response to rainfall was more accentuated nearer the top boundary. The groundwater depth was about 2 m in the rainy season (Figure 5(b)) and the hydraulic conductivity of soil was low (2.9×10^{-4} cm s^{-1}). Consequently, the vertical recharge to groundwater from the ground surface was limited. The vertical water transport in the vadose zone (infiltration and evaporation) was limited and the lateral groundwater flow was dominant in at this site. Salt accumulation is usually an unavoidable problem in arid environments. However, lateral flow prevents salt accumulation and hence salinity problems have not been reported in the Liudaogo basin.

Figure 7 shows daily rainfall and GWL at G1 for two rainfall events. As seen from the figure, there was a time lag between rainfall and GWL peaks corresponding to a few days. An isolated rainfall event (24.4 mm) occurred on August 23rd, 2005. The peak of the GWL for this event was on the 25th. There was consequently a 2-day time lag between rainfall to peak of the GWL. The lower part of the figure shows a GWL peak on August 14th, 2006 to the rainfall of August 9th, 10th (44.6 mm), and 12th (6.8 mm). The rise of the GWL was about 0.2 m.

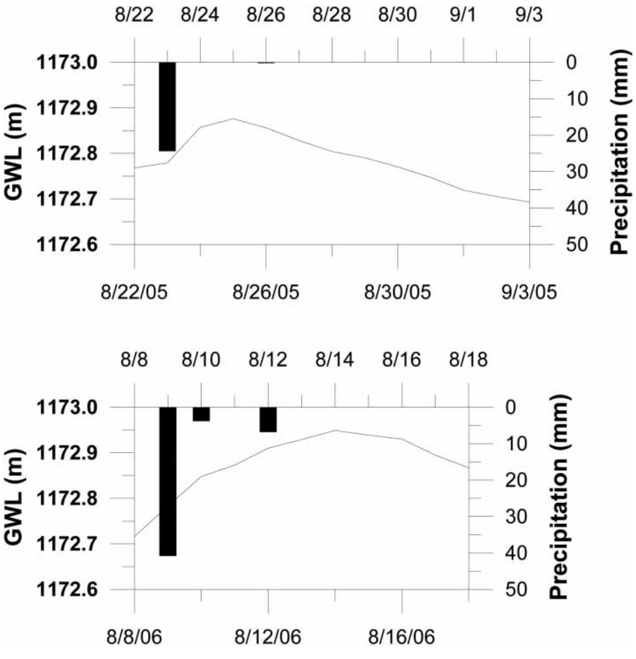

Figure 7 | Daily groundwater level (GWL) at G1 and daily precipitation. Since GWL is plotted as a daily value, diurnal fluctuations are not shown.

According to the above, recharge of groundwater in the dam farmland was caused by ephemeral runoff from the upstream hilly area in the rainy season. Vertical recharge was much less and the lateral flow was dominant in the study area and there was a time lag of about 2 days between rainfall and GWL recharge. The time lag of other wells (G2 and G3) was about 3 days (Figure 8).

Estimation of recharge

The recharge was estimated based on GWL fluctuations by the 'water table fluctuation method' (e.g., Healy & Cook 2002):

$$\mathrm{Rec} = S_{\mathrm{y}} \frac{\Delta h}{\Delta t} \tag{1}$$

where Rec is recharge, S_{y} is specific yield, h is GWL height, and t is time. This method is based on the premise that rise in GWL is due to recharge water arriving at the water table. Equation (1) assumes that water arriving at the water table turns immediately to recharge going into storage and that all other components concerning the recharge such as base-flow, evapotranspiration, and change in subsurface storage are zero during the period of recharge. Consequently, this method is mainly valid over short periods of time, up to a few days (Healy & Cook 2002).

The GWL at G1 was exposed to water uptake by surrounding grass and shrubs during the growing season. Consequently, application of the water table fluctuation method does not satisfy the above assumption that evapotranspiration was zero. Thus, it should be noted that we separate groundwater recharge from plant water uptake below. The specific yield S_{y} depends on the soil type. The aquifer below the farmland is formed by a layered structure of loamy sand and sandy loam (Zheng 2004). Loheide

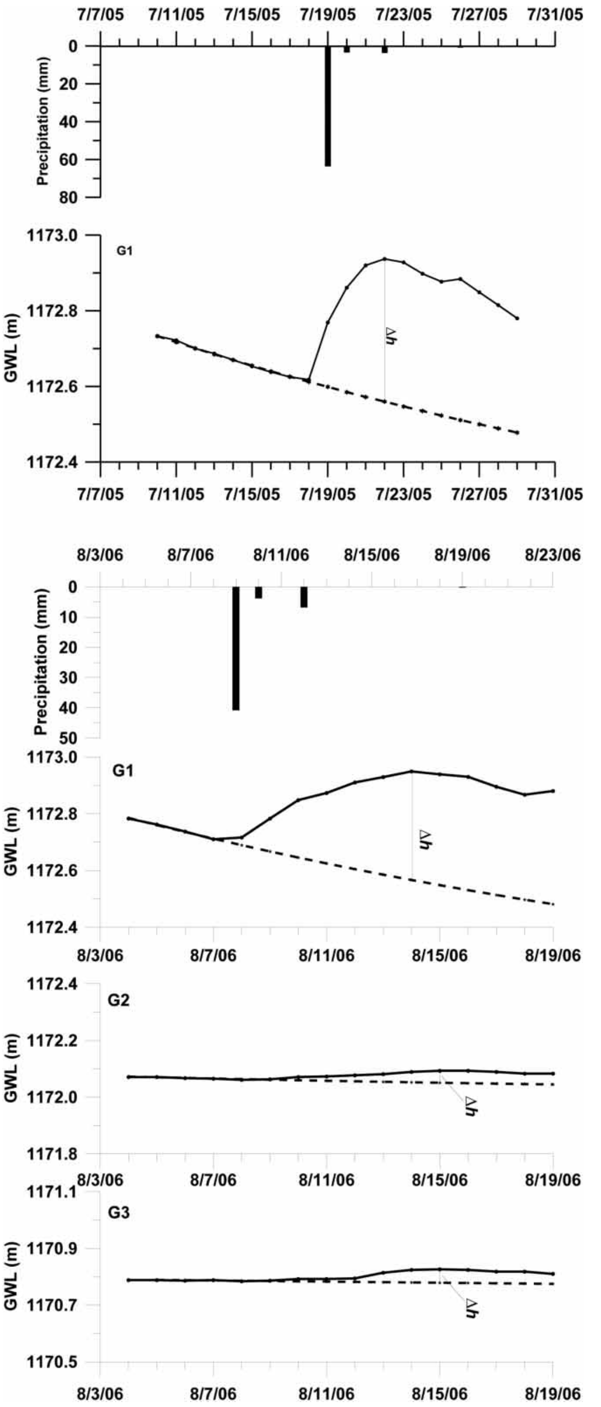

Figure 8 | Response of the daily GWL to precipitation event. Precipitation and GWL are given as daily values.

et al. (2005) quoted values of S_y due to soil type based on Johnson (1967). Based on this information $S_y = 0.23$ was applied and recharge amount was estimated for six isolated rainfall events according to Table 1. To evaluate the rise of the GWL, Δh in Equation (1), the recession curves were interpolated by an exponential function and the curve was extended as shown in Figure 8.

The estimated recharge ratio (recharge/precipitation) of G1 was 0.309–0.942 according to Table 1. The ratio was low, 0.443, in June 2006, in the beginning of the growing season and it increased to 0.942 in August, at the end of the growing season. GWL data from G2 and G3 were limited and only a few recharge estimations could be done. The recharge ratio of G2 and G3 was consistently small. The recharge as a response to intensive rainfall was caused by inflow from the upstream hilly area. The width of the study site is narrow at the top boundary (at G1) and the width increases at G2 and G3 (Figure 1, Figure 3(a)). Therefore the recharge ratio of G2 and G3 was much smaller than that of G1. The response of GWL to recharge was limited and only clearly evident for intensive rainfall during the rainy season. Recharge ratio varied during the observation period and appeared to increase later in the rainy season.

Diurnal fluctuation by plant water uptake

Figure 9 shows rainfall, GWL (G1), temperature, and solar radiation from the end of August to the beginning of September in 2005. The diurnal fluctuation was seen only for GWL of G1. GWL of other wells did not indicate such a diurnal fluctuation. Since G1 was surrounded by shrubs (Figure 4), the GWL of G1 indicated the diurnal fluctuation due to water uptake by the shrubs. GWL of other wells (G2 and G3) did not indicate the diurnal fluctuation. The GWL of G1 indicates a clear diurnal fluctuation. After sunrise, the GWL begins to decline due to increasing temperature and solar radiation and it starts to recover again after sunset.

The GWL increased and reached a peak 3 days after the rainfall event on August 23rd. After the GWL reached a peak it repeated the diurnal fluctuation. The peak and bottom values continued to decrease. However, even though there was not any rainfall on September 4–6th, the GWL showed a slight rise corresponding to the decrease in temperature and solar radiation and the resulting reduced plant water uptake due to a cloudy period. Thus, it is clear that diurnal fluctuation of GWL is sensitive to temperature and solar radiation variation.

Table 1 | Estimation of recharge

Precipitation event		**2005/7/19**	**2005/8/23**	**2006/6/23**	**2006/7/4**	**2006/8/9**	**2006/8/25**
Precipitation (mm)		70.8	24.4	48.2	19.0	51.4	20.2
Recharge (mm)	G1	21.9	18.4	9.3	11.7	44.0	19.0
	G2	–	–	–	–	3.2	4.5
	G3	–	–	–	–	3.6	–
Recharge ratio	G1	0.309	0.753	0.415	0.617	0.856	0.941
	G2					0.062	0.223
	G3					0.070	

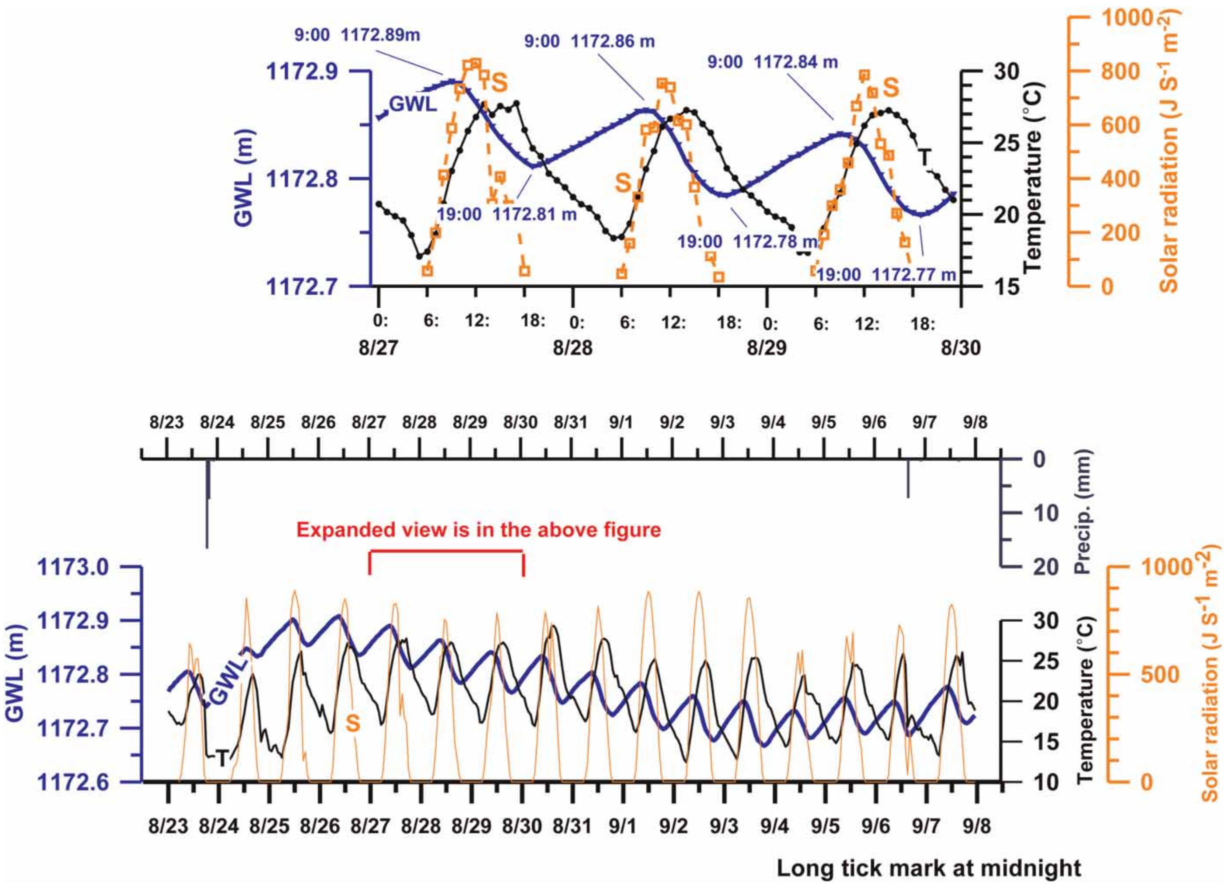

Figure 9 | Diurnal fluctuation of hourly groundwater level (GWL) at G1, temperature (*T*), and solar radiation (*S*) (August 23–September 8, 2005).

To illustrate details of diurnal groundwater fluctuations, hourly GWL at G1, temperature, and solar radiation from August 27th to 29th are shown in the upper part of Figure 9. The graph shows that the decline of GWL was clearly synchronized with the solar radiation. After sunrise the GWL started to decline at morning 09:00 when the solar radiation increased and temperature exceeded 20 °C. It continued to decline until sunset at the evening 19:00. After sunset the GWL started to recover slowly and it continued to recover until the next morning at about 09:00. This diurnal fluctuation formed a cyclic pattern of decline in day time and recovery in night time.

The daily difference between the highest and the lowest value of the GWL during this period was approximately 0.08 m. There was no rainfall and only the plant water uptake affected the GWL. The daily peak value decreased approximately 0.02 m per day in this period. Consequently, the link between GWL and the solar radiation is apparent. A strong diurnal fluctuation by plant water uptake is, however, only clearly seen at G1. The observation well G1 is located near the top end of the farmland where the valley width is narrow and sediment depth above the original valley stream is shallow (about 2 m; Figure 1, Figure 4). Shrubs (*Salix matsudana*) were growing around G1 and their roots are evidently able to take up groundwater.

The capillary rise of soil in Liudaogo is less than about 0.5 m (Zheng 2004). Groundwater depth during the growing season was about 2 m. Evaporation from the water table through soil profile is limited because of low capillary rise. Transpiration through the shrubs is thus expected to be much larger than evaporation through the soil profile.

On cloudy days, temperature and solar radiation were low and the daily highest and lowest GWL increased above the corresponding values for the previous day even if there was no rainfall. Consequently, there was a large influence from the plant water uptake on the GWL diurnal fluctuation. The effect of temperature was more pronounced on the seasonal fluctuation for the GWL during a year and that of solar radiation was more affected on the diurnal fluctuation of the GWL during the growing season.

Commencement and termination of the water uptake

As described in the previous section, plant water uptake appeared to have a significant effect on the GWL fluctuations. The commencement and termination of fluctuations are consistent with that of the plant water uptake in spring and autumn. Figure 10(a) shows the GWL at G1 with daily maximum and minimum temperature and hourly precipitation from May to June in 2005. The diurnal fluctuation became apparent approximately at the end of May. However, prior to the diurnal fluctuation, decline of GWL at all three wells had started according to Figure 6. Figure 10(a) indicates that the diurnal fluctuation commenced around May 19th, 2005. Some diurnal fluctuation, however, was also found during a few days after May 11th and this disappeared on the 15th. The diurnal fluctuation appeared to set in when the minimum temperature was above 8 °C for a period of

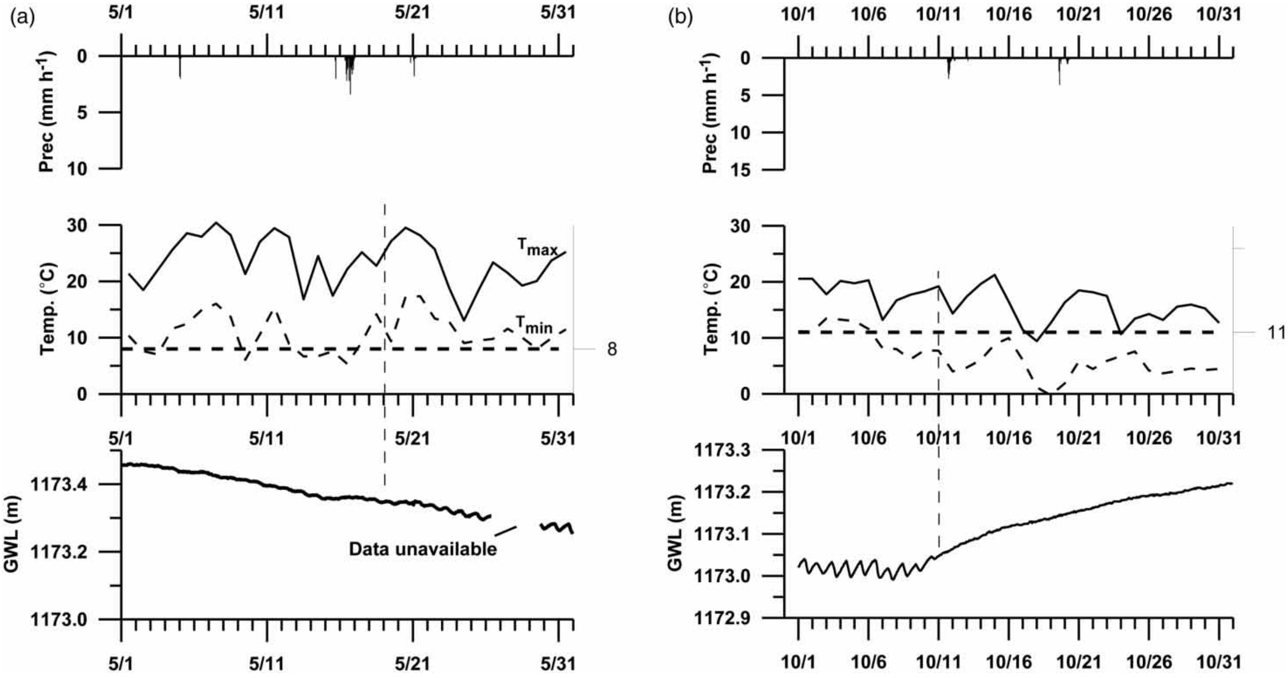

Figure 10 | (a) Commencement of diurnal fluctuation at G1 and daily temperature and precipitation (May 2005). (b) Termination of diurnal fluctuation and recovery of the groundwater level at G1 and daily temperature and precipitation (October 2005).

4–5 days. After that the fluctuation became stronger as the temperature increased. The total decline of the GWL for these two months was approximately 0.5 m.

Figure 10(b) shows the hourly fluctuation of the GWL at G1 with hourly rainfall and daily maximum and minimum temperature during the recovery process. According to Figure 10(b), the day of termination is October 11th, 2005. The maximum and minimum temperature on October 11th, 2005 was 19.2 and 7.7 °C, respectively. The termination of diurnal fluctuation was observed when the minimum temperature was below 11 °C and for 4–5 days. In October 2005, the minimum temperature became less than 11 °C on the 7th and 4 days after this the diurnal fluctuation terminated. *Salix matsudana* becomes dormant (prior to leaf loss), resulting in a significant decrease in water uptake. Consequently, the termination is more apparent as compared to the commencement. Timing of the termination coincided well with that of groundwater recovery in the farmland.

The commencement of diurnal fluctuation occurred when the minimum temperature was no longer below 8 °C. The termination of the diurnal fluctuation occurred when the minimum temperature remained below 11 °C for several days. The recovery of the GWL thus started by the ending of the plant water uptake. This is also in agreement with previous observations: 'The sudden decline in water-table fluctuations can be linked to a sudden drop in minimum temperature that may have triggered plants into dormancy' (Lautz 2008). At the farmland in the Chinese Loess Plateau, the minimum temperature trigger that stopped the diurnal GWL fluctuation appears to be 11 °C. Temperature change in spring and autumn appears to function as a trigger both for the commencement and termination of the plant water uptake.

CONCLUSIONS

Filled-up check dams contain level and fertile farmland with shallow groundwater that can be used for agricultural development in arid Chinese environments. The shallow groundwater could be a promising water resource. The shallow groundwater in the dam farmland is recharged by inflow from the upstream hilly region. Considering the water budget, the groundwater can be used for sustainable agricultural activity at the Chinese Loess Plateau. Prior to this development, however, groundwater fluctuation due to recharge and plant water uptake must be evaluated. In this study, the following three conclusions can be made.

Regarding the effect of plant water uptake on seasonal GWL fluctuation, there was a large impact of plant water uptake on GWL fluctuation in the small field site. The GWL in the farmland was drawn down by plant water uptake during the growing season from April to September and then recovered during the winter. The effect of temperature was more pronounced on the seasonal fluctuation for the GWL during a year, while that of solar radiation was more important for the diurnal fluctuation of the GWL during the growing season.

With respect to recharge, occasionally ephemeral runoff originating in the upstream hilly region from intensive rainfall and runoff flowed into the dam farmland as a waterfall at the top boundary. Groundwater in the dam farmland was recharged by this ephemeral inflow. However, in general, GWL rise due to recharge was small relative to GWL drawdown by plant water uptake during the growing season.

Finally, diurnal fluctuation of the GWL due to plant water uptake was monitored near the upstream end of the site for 2 years (2005–2006). During the growing season, the GWL declined during the daylight hours and recovered during night time. The diurnal fluctuation was well synchronized with solar radiation. The diurnal fluctuation was caused by shrubs (*Salix matsudana*) and grass surrounding the observation well at the upstream end of the site. While the termination of the diurnal fluctuation in autumn was apparent, the commencement in spring was not as clear. The commencement of the diurnal fluctuation occurred when the minimum temperature rose above 8 °C. The termination of the diurnal fluctuation occurred when the minimum temperature remained below 11 °C for several days. *Salix matsudana* becomes dormant prior to leaf loss, so significant decrease of water uptake was observed prior to leaf loss. The termination of the diurnal fluctuation was more apparent as compared to the commencement. Timing of the termination coincided with that of groundwater recovery in across the field site.

The present study showed that plant water uptake by shrubs had a significant effect on diurnal and seasonal groundwater level variations. The diurnal and seasonal effects were closely correlated with solar radiation and temperature variations, respectively. These effects may have influence on shallow groundwater storages used as water supply for local communities.

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