

## Soil water dynamics and deep soil recharge in a record wet year in the southern Loess Plateau of China

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### ARTICLE INFO

#### Keywords:

Soil water recharge  
Eco-hydrology  
Loess Plateau  
Dryland farming

### ABSTRACT

Terrestrial water cycles are influenced by hydrologic and textural properties of the deep loess layer in the Loess Plateau. Analyses of soil water profile distributions are needed to understand the regional water cycle processes and to guide agricultural production and sustainability. The objective of this study was to quantify the extent of deep soil water recharge and soil water profile dynamics during 1987–2003, especially in a record wet year of 2003, in common cropping systems in a semiarid-subhumid region of the southern Loess Plateau. The Chinese Ecological Research Network (CERN) site and a long-term rotation experiment site in a flat tableland were selected for this study. Soil moisture profiles were measured by a neutron probe to a depth of 6 m in 2003. The precipitation of 954 mm at the Changwu County Meteorological Station in 2003 was 63.4% higher than the long-term average (584 mm), and was a record high since 1957. Although cropping systems affected deep soil water recharge, the persistent dry soil layer formed between 2- and 3-m depths in croplands, resulting from many years of intensive cropping, was fully replenished in all cropping systems in 2003. Further frequency analysis indicated that the desiccated layer between 2- and 3-m depths would be fully recharged at least once in about 10 years for all existing cropping systems excluding continuous alfalfa. This finding should alleviate concerns about the formation of a permanent deep-soil desiccation layer as well as its potential impact on the long-term sustainability of the existing intensive cropping systems in the region.

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### 1. Introduction

Soil water dynamics are strongly affected by land use/cover in the Loess Plateau (Chen et al., 2007). Precipitation is the key factor limiting agricultural production in the region. Precipitation is the main water source for agriculture, and therefore efficient use of limited rainwater to improve crop yield has long been the primary research focus. Years of intensive farming by increasing fertilization and implementing yield-enhancing management practices have led to the gradual depletion of soil water or soil desiccation between 2- and 3-m soil depths due to high plant water use (Li, 2001b). The dry soil layer was defined as the soil layer that has soil moisture ranging between the wilting point and a steady soil moisture level, normally less than 75% of field capacity (Li, 2001a). Such multi-year soil water deficit has raised the concerns of many

soil scientists and agronomists on whether the desiccated soil layer can be fully recharged under the existing continuous cropping systems as well as the potential impacts of the dry soil layer on crop yields and the sustainability of the current production systems in the region.

Selection of a soil profile depth (or control volume) is crucial for calculating field water balance, which is useful to estimate total plant available water, crop yield, and extent of soil water depletion by a crop or recharge under a certain climate condition. Maximum rooting depth and maximum wetting depth of rainwater are the two primary depth parameters for selecting a soil profile depth. The former is determined by the vegetation type (Hodnett et al., 1995; Williamson et al., 2004), and the latter by the amount of precipitation and antecedent soil water deficit in a soil profile (Wright and Black, 1978). Li et al. (1985) reported that for evapotranspiration (ET) estimation of annual field crops including winter wheat, maize, sorghum and cotton in the Loess Plateau area, a soil depth of no less than 2 m should be used because more than 90% of ET normally comes from this zone. Considering that field

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soil water profile measurement is labor-intensive and time-consuming, a soil thickness between 2 and 3 m should be sufficient for estimating field water balance in the region in years having average or below-average precipitation. This recommendation implies that significant soil water recharge generally would not occur beyond 2–3 m depth. In wet years, however, the wetting depth of infiltrated rainwater may exceed 2 or even 3 m, and amounts infiltrated below this depth may become significant. Thus, the 2–3 m soil depth recommended for water balance calculation needs to be reexamined for wet years in the study region.

To characterize water recharge into deep soil layers or maximum wetting depth of rainwater, it is necessary to know the initial water deficit in a soil profile, precipitation, and total ET (or plant water use) under common cropping systems in years with above-average precipitation, especially in extremely wet years. The objective of this study is to quantify the extent of deep soil water recharge and soil water profile dynamics in common cropping systems in a semiarid-subhumid region of southern Loess Plateau using field measured data during 1985–2003, especially in the record wet year of 2003.

## 2. Materials and methods

### 2.1. Study region

The Changwu tableland region is situated in the tableland-gully region of southern Loess Plateau, in the middle reaches of the Yellow River in northern China (Fig. 1). The tableland-gully landscape is one of the main topographic-ecological units in the Loess Plateau, which consists of two geomorphic subunits: tableland and dissected tableland. The Changwu Agro-ecological Experiment Station, 2.5 km west of the Changwu County Meteorological Station, is located in the Wangdonggou experimental watershed in the Changwu tableland region. The Wangdonggou watershed is comprised of 35% tableland and 65% dissected land. The farmlands are mainly distributed in the flat areas of the tableland and dissected lands. The wheat–wheat–maize rotation and continuous wheat are the most common cropping systems in the region.

### 2.2. Site description and cultural practices

The Changwu Agro-ecological Experiment Station (35.2°N and 107.8°E) is located in the warm temperate zone, and has a

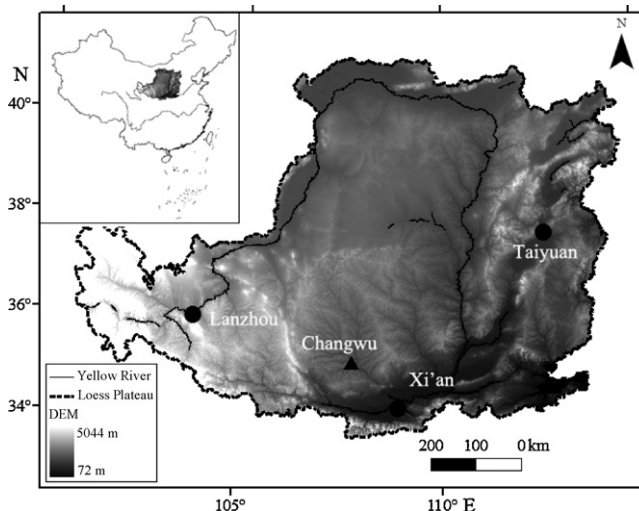


Fig. 1. The location of Changwu Agro-ecological Experiment Station.

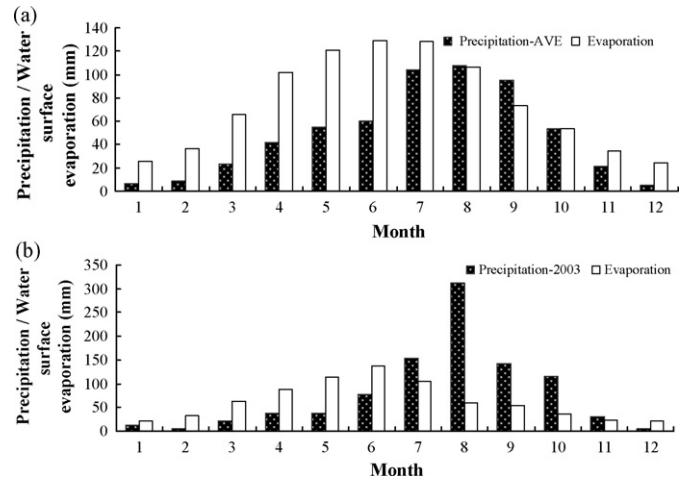


Fig. 2. Monthly precipitation and E601 pan evaporation (Evaporation) at the Changwu County Meteorological Station: (a) average from 1957 to 2003 and (b) year 2003 only.

continental monsoon climate. The experimental sites are in a flat farmland on the Changwu tableland. The elevation is 1200 m above sea level. The average annual precipitation is 584 mm, with 55% falling from July through September (Fig. 2a). The annual average temperature is 9.2 °C. The soil is light silt loam (Heilutu series). The soil properties including soil texture, bulk density, field capacity, and wilting point, are shown by layer in Table 1. The overall depth-averaged bulk density of the soil profile was 1.3 g/cm<sup>3</sup>, the field capacity is 22.5% by weight (g/g) or approximately 29% by volume (m<sup>3</sup>/m<sup>3</sup>), and the wilting point is 7.5% (g/g) or approximately 9.8% by volume (m<sup>3</sup>/m<sup>3</sup>) (The soil water content in this paper is on a mass basis, unless stated otherwise). The ground water table was 80 m below surface.

Two experimental fields, 5 km apart, were selected for this study. One was on the comprehensive experimental site of the Chinese Ecological Research Network (CERN), which was under a winter wheat–wheat (+broom corn millet)–maize rotation. The winter wheat in the second-year rotation was double cropped with broom corn millet in some years. In 2003, the first-year winter wheat was harvested in June, and the second year wheat was planted in October, with summer bare fallow in between. The field was moldboard plowed to a 20-cm depth in late June after wheat harvest, hoed to a 5-cm depth in mid-August, and rotor tilled to about 20 cm in mid-September before wheat planting. Nitrogen (120 kg N/ha in the form of urea) and phosphorus (60 kg/ha P<sub>2</sub>O<sub>5</sub>) were applied and incorporated by a rotary tiller before wheat planting. The other field was on the Changwu long-term rotation experiment site. Cropping systems selected for comparisons include continuous winter wheat, alfalfa, and bare-soil fallow, as well as wheat (+broom corn millet)–pea–wheat rotation. In 2003, pea (*Pisum sativum* L.) was planted into bare soil in April and harvested in July, and wheat was planted in October for the rotation of wheat (+broom corn millet)–pea–wheat. Tillage operations varied with cropping systems. Generally, each field was moldboard plowed after harvest and rotor tilled before planting with shallow tillage to remove weeds during fallow or growing season as needed. The fertilizer treatments were check (no fertilization), (N + P)-mixed fertilization at the rates of 120 kg/ha N and 60 kg/ha P<sub>2</sub>O<sub>5</sub>, and N + P + manure application at the rates of 120 kg/ha N, 60 kg/ha P<sub>2</sub>O<sub>5</sub> and 75 ton/ha organic manure.

### 2.3. Measurement methods

Soil moisture content down to a depth of 6 m was measured with a neutron probe. There were three plots for each treatment,

**Table 1**  
Selected soil physical properties of Heilutu series by depth.

Soil depth (cm)	Particle size (%)			Bulk density (g/cm <sup>3</sup> )	Field capacity (w/w %)	Wilting point (w/w %)
	<0.01 (mm)	0.01–0.001 (mm)	<0.001 (mm)			
0–40	37.0	20.5	16.6	1.34	21.6	6.7
40–100	46.0	24.2	21.8	1.34	22.1	8.5
100–185	42.3	21.9	20.4	1.26	23.3	7.9
185–230	39.7	21.3	18.5	1.29	22.6	7.3
230–300	40.6	24.3	16.3	1.31	22.3	7.0

with one access tube centered in each plot (10.3 m × 6.5 m). Measurements were made once a month on the long-term rotation site and three times a month on the CERN site. The neutron probe was calibrated against gravimetrically measured soil moisture contents using soil cores. The meteorological measurement location of the CERN site was near the study fields. A rain gauge (diameter 20 cm) and a standard E601 pan evaporator denoted as E601-1 by Fu et al. (2004) were maintained on the site.

Annual wetting depth ( $D$  in mm) in the Loess Plateau is a function of (1) precipitation during rainy season,  $P$  in mm, (2) actual ET in the rainy season in mm, and (3) volumetric soil water deficit relative to field capacity prior to the rainy season,  $\theta_d$  (cm<sup>3</sup>/cm<sup>3</sup>). The wetting depth can be estimated by

$$D = \frac{P - ET}{\theta_d} \quad (1)$$

if the surface runoff component is neglected (Li, 1983). This assumption is approximately valid in the tableland area since the slope is near zero, and runoff is negligible. Song et al. (2000) reported that annual runoff accounted for 0–2% of annual precipitation in the experimental plots (5 m × 20 m) with slopes lower than 1° in the Changwu tableland region.

#### 2.4. Frequency analysis

Frequency analysis of deep soil water recharge was conducted using long-term records of annual precipitation of 1957–2003 at the Changwu County Meteorological Station and maximum wetting depths measured during 1987–2003 for selected cropping systems. First, a linear regression was fitted between yearly maximum recharge depth and annual precipitation depth for the period of 1987–2003. Since the maximum recharge depth occurred in October each year, the annual total precipitation (summation of daily precipitation from October 1 of the previous year to September 30) was used in the regression. The fitted function was used to compute the maximum wetting depths using annual precipitation for the years of 1957–2003. Second, the estimated yearly maximum recharge depths during 1957–2003 were ranked in a descending order, and the frequency ( $P_f$ ) was computed as

$$P_f = \frac{m}{n+1} \times 100\% \quad (2)$$

where  $m$  is the descending order, and  $n$  is the total number of years ( $n=47$ ). Third, a Pierson Type III function was fitted to the frequency curve to obtain a theoretical distribution, which was then used to estimate frequency for any chosen recharge depth. Fourth, a return period for a given recharge depth was calculated as  $100/P_f$ .

### 3. Results

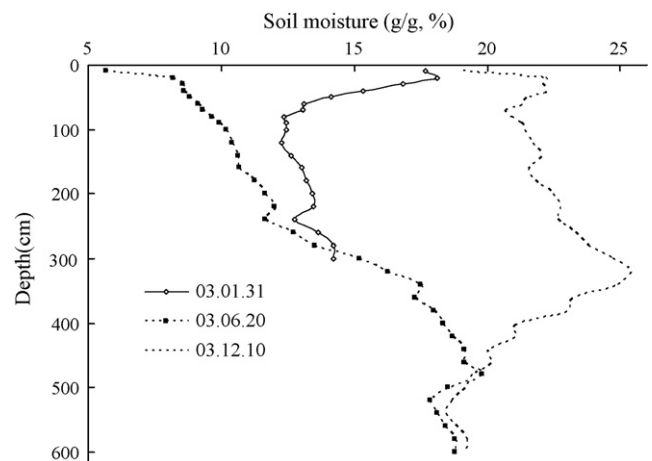
#### 3.1. Precipitation

The long-term average annual precipitation measured at the Changwu County Meteorological Station was 584 mm, and average annual pan evaporation was 892 mm. In 2003 the precipitation

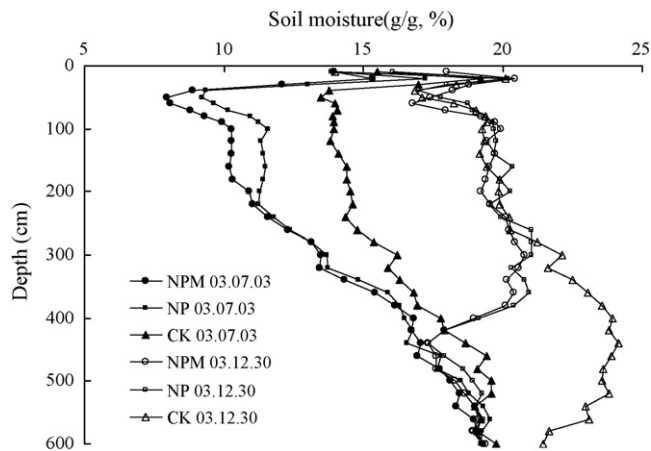
measured at the County Station was 954 mm, which set the record since 1957 and exceeded the long-term average by 63.4%. The total pan evaporation in the year was 757 mm. In the same year, the precipitation measured at the CERN site was 830 mm, and the total pan evaporation was 726 mm. The monthly precipitation and pan evaporation in 2003 as well as the long-term averages measured at the Changwu County Meteorological Station are shown in Fig. 2. The rainy season was from July to September, during which soil water recharge occurred (Fig. 2a), and the recharge was more profound in the wet year 2003 (Fig. 2b). Monthly precipitation in 2003 was less than pan evaporation from January thru June, but the opposite was true from July to November, which was the main soil water recharge period of a year.

#### 3.2. Soil water profile dynamics

The vertical distribution of soil water in a profile is a function of many factors such as antecedent moisture content, precipitation amount, weather conditions, and crop growth (Wright and Black, 1978). Soil water distribution within the profile results from the combined effects of vertical movement of soil water and plant water uptake. Soil water profiles measured in January, June, and December of 2003 on the CERN site under wheat–wheat–maize rotation are shown in Fig. 3. As mentioned above, winter wheat was harvested in June and then planted again in October with bare-soil fallow between June and October. Soil water storage between 0- and 2.5-m depths was greatly reduced in June compared with January due to water uptake by the first-year wheat. From the soil water depletion curves, an apparent maximum rooting depth of 2.5 m could be assumed, which was similar to the maximum depth of 2.7 m observed in soil pits or cores in the region (Li et al., 1985). Dardanelli et al. (1997) successfully used this soil water depletion technique to identify the apparent rooting depths for several crops during the growing seasons. Comparing the soil water profiles of June and December, the wetting front reached to a depth of 5 m in



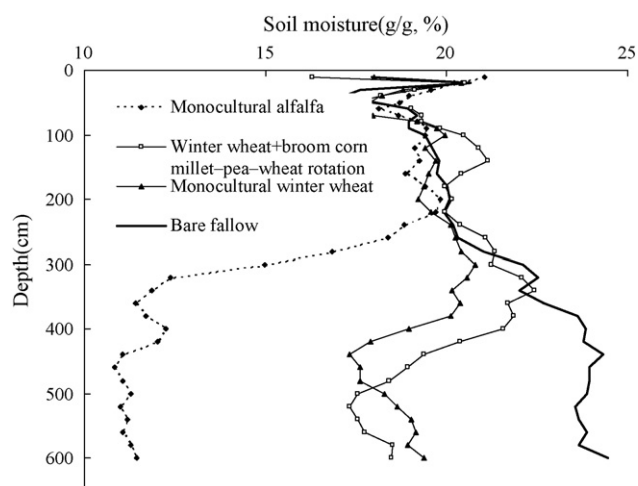
**Fig. 3.** Soil water profile distribution in a second year of winter wheat in a wheat–wheat–maize rotation on the CERN comprehensive experiment site in 2003 (legend: yy.mm.dd).



**Fig. 4.** Soil water profile distribution in the monocultural winter wheat on the long-term rotation experiment site at three fertility levels on July 3 (beginning of the rain season) and December 30 of 2003 (NPM = nitrogen, phosphorus, manure; CK = check (no fertilization); legend: yy.mm.dd).

such a wet year, indicating the complete recharge of the entire soil profile under this predominant cropping system in the region. Detailed comparison of the measured monthly soil water profiles (data not shown) indicated that the wetting front on this site reached a depth of 1.5 m by late July, 2 m by late August, 2.5 m by mid-September, 3 m by early October, 3.5 m by mid-October, 4 m by the end of November, and 5 m by the end of December. Soil water storage between 3- and 6-m depths increased by 90 mm from early October to the end of December.

Soil water profiles on the long-term rotation experimental site under the continuous wheat, alfalfa, and fallow, as well as wheat rotation are shown in Figs. 4 and 5. By the end of December 2003 in the continuous wheat system, the wetting front reached a depth of 4.5–5.0 m under N + P and N + P + manure fertilization (NPM treatment) and deeper than 6 m under no fertilization (Fig. 4). The total soil water recharge depths within the 6-m profile were 397, 377, and 371 mm for the NPM, NP, and CK treatments, respectively, between July 3 and December 30 in 2003. The recharge depths for NPM and NP were inversely related to the soil moisture contents on July 3 and during the recharge period, largely resulting from lesser soil evaporation at lower soil moisture level.



**Fig. 5.** Soil water profile distribution in the monocultural winter wheat, winter wheat (+broom corn millet)-pea-wheat rotation, and monocultural alfalfa with balanced supplies of nitrogen, phosphorus and organic fertilizers, and in the bare fallow on the long-term rotation experiment site in December of 2003.

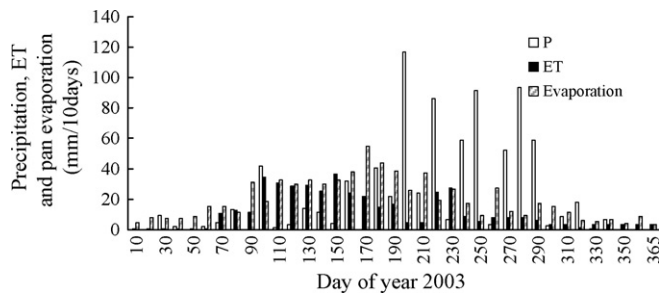
The deeper percolation in the no-fertilizer treatment was due to lower water consumption by wheat plants under no fertilization.

These results are consistent with those of others. Wright and Black (1978) reported that N-fertilized grasses extracted more water from the soil profile than did unfertilized grasses throughout the year. Cubera and Moreno (2007) also reported that soil water content was significantly lower in the fertilized crop plots than in the unfertilized crop plots. In the N + P + manure treatment, the soil water profiles under the wheat (+broom corn millet)-pea-wheat rotation (note pea and wheat were grown in 2003) and the continuous wheat were quite similar by the end of December, and soil water content increased to the 5-m depth (Fig. 5). Under the continuous alfalfa, the wetting front reached near the 3-m depth, and soil water contents below this depth were near the wilting point and were much lower than those of other treatments, indicating that the groundwater recharge under continuous alfalfa was negligible in the region. This result showed that (1) perennial alfalfa extracted soil moisture as deep as 6 m and probably even deeper, (2) subsoil moisture restoration below 3 m is unlikely under continuous alfalfa in the region, (3) crop rotation or a certain length of fallow period is necessary to replenish subsoil moisture below 3 m, and (4) the monocultural wheat with sufficient fertilization is the second most water-consuming system of all cropping systems in the region (Figs. 4 and 5). Li et al. (1985) reported that the maximum rooting depth of alfalfa was about 5 m, and soil water extraction could reach below 6 m due to capillary rise. Grandfield and Metzger (1936) found that 27 months of alfalfa removed all available moisture to deeper than 6 m at Manhattan, Kansas when annual precipitation was around 580 mm. Bullied and Entz (1999) reported that alfalfa crops, due to their deep roots and high water demand, tended to dry the soil profile and cause water shortage in the subsequent crops. Under continuous fallow on the CERN site, on the other end of the spectrum, the wetting front reached beyond the 6-m maximum measurement depth by the end of December, indicating that groundwater recharge occurred under the fallow system in wet years. The much deeper wetting depth in the continuous fallow is due to the high antecedent moisture content in the soil profile prior to the rainy season. Chang et al. (1990) reported that soil water content in deep subsoil layers was significantly greater under fallow than under crops, showing that soil water recharge was deeper in fallow fields than in cropped fields. The total soil water storage depths within the 6-m profile on December 30 after recharge (Fig. 5) were 1180, 1497, 1548, and 1690 mm for the monocultural alfalfa, monocultural winter wheat, wheat-pea-wheat rotation, and bare fallow, respectively. The total water storage was inversely related to water consumption intensity of the crop, indicating the persistency of water recharge deficit under intensive cropping.

### 3.3. Evapotranspiration (ET) estimation

Assuming no surface runoff or deep percolation below the control volume, actual ET can be estimated as the difference between precipitation amounts and changes in soil water storage. The assumption of zero surface runoff is reasonable because the field plots were flat and each plot was surrounded by ridges. Pondered water after heavy rains was rarely observed to flow beyond the plot boundaries. The validity of negligible deep percolation depends on the maximum depth used in calculation, which is discussed below. Such water balance calculation tends to overestimate ET, if soil water percolates below the maximum calculation depth and the percolated water is neglected. In general, the maximum calculation depth usually used in ET estimation in the Loess Plateau was between 2 and 3 m. As presented above, on the CERN site, soil water recharge reached deeper than 3 m by early October, thus the maximum calculation depth used in the water





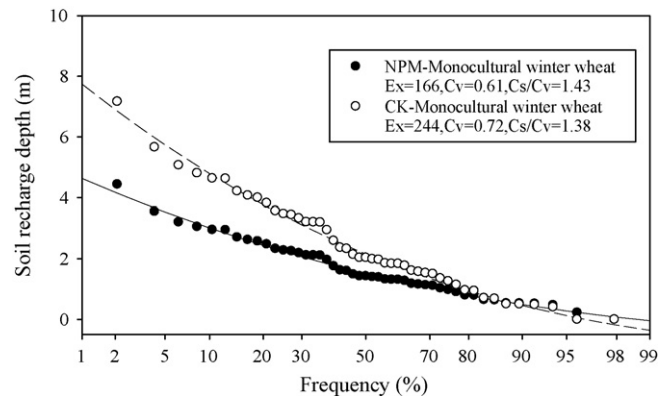
**Fig. 6.** Temporal variation of precipitation (P), estimated evapotranspiration (ET), and measured E601 pan evaporation (Evaporation) in 10-day intervals in the winter wheat field on the CERN experiment site in 2003.

balance estimation after October must be greater than 3 m. By the end of December, the wetting front reached the 5-m depth (Fig. 3). The ET estimation using the 6-m depth as the maximum measurement should yield reliable results for all treatments except in the continuous bare fallow and low-yield fields. The estimated ET on the CERN site using the water balance method and 6-m calculation depth is shown in Fig. 6 in 10-day increments for the entire year. Prior to day 180, ET, dominated by wheat transpiration, was generally greater than precipitation, indicating net soil water depletion by wheat during the period. After day 180, ET, primarily determined by soil evaporation during the bare fallow, was greatly reduced and was much less than precipitation, which resulted in significant soil water recharge. The seasonal pattern of the pan evaporation mirrored that of the actual ET, which was about 60% of the total pan evaporation (Fig. 6). The total ET in 2003 was 428 mm, of which 139 mm was lost through soil evaporation during the bare fallow (note that 648 mm of precipitation occurred in the same period). As presented above, soil water content between 3 and 6 m increased by 91 mm (average soil water content of 0.03 m/m) from early October to the end of December. Thus, if the maximum depth of 3 m was used as normally recommended in the water balance calculation, the total ET would be overestimated by 91 mm. The relative error would be 21%, which is unacceptable for either research or practical applications.

#### 4. Discussion and implication

In studying field soil water dynamics and crop–water relations, the water balance method is commonly used to determine ET and other hydrologic components (Johnsson and Jansson, 1991; Hodnett et al., 1995). A key parameter in the computation is the maximum soil depth or soil layer thickness, which is determined by the maximum rooting depth and the maximum wetting depth of rainwater.

Prior to the rainy season in 2003, average soil moisture contents between the soil surface and 2-, 3-, 4-, and 5-m depths were 9.9, 10.9, 12.6, and 13.9% (g/g) on the CERN site, respectively. The corresponding moisture deficits on a volume basis were 16.4, 15.1, 12.9, and 11.2%. Based on Eq. (1), 328, 452, 515, and 559 mm of water were needed to wet the soil profile to the depths of 2, 3, 4, and 5 m, respectively. In 2003, total precipitation during the summer fallow at the Changwu station was 648 mm, and ET of the same period was 139 mm, with a difference of 509 mm. Based on this calculation, the wetting depth would only reach to the 4-m depth. However, the measured wetting depth was about 5 m (Fig. 3). The discrepancy was caused by dispersion across the wetting front driven by its suction potential gradient and less than field-capacity water content in the end of the recharge period due to soil water redistribution. The water balance method would overestimate ET if a considerable amount of water penetrates



**Fig. 7.** Exceedance frequency distribution of estimated maximum soil recharge depths under optimally fertilized wheat (NPM-monocultural wheat) and unfertilized wheat (CK-monocultural wheat). The lines are theoretical distributions best fitted to Pierson Type III functions ( $Ex$  = expected value,  $Cv$  = coefficient of variation, and  $Cs$  = skewness coefficient).

below the control volume. Overall results showed that the soil water profile was fully replenished below the 3-m depth under the typical crop rotations in 2003 and the soil desiccation between 2 and 3 m was a persistent but not a permanent phenomenon. This result has a general implication for developing sustainable water management practices in the region.

To complement the recharge results obtained from the wettest year of 2003, frequency analysis of deep soil water recharge was conducted using long-term records of annual precipitation of 1957–2003 and maximum wetting depths measured during 1987–2003 in the continuous winter wheat with and without sufficient fertilization (NPM and CK treatments, respectively, in Fig. 4). These two treatments were chosen because (1) the soil water profile measurements were relatively complete and frequent during the period allowing adequate identification of the maximum wetting depth in each year, and (2) the treatment of continuous wheat with sufficient fertilization was the second most water-consumptive system after alfalfa in the region as mentioned above. Thus, any recharge frequency drawn from this system, though conservative, would be applicable to the other systems and indicative of the maximum period between two possible recharge events in the region.

The coefficients of determination of the linear regression between yearly maximum recharge depths and the corresponding annual precipitation amounts were 0.834 for both sufficiently fertilized and unfertilized treatments. The fitted equations were used to estimate the yearly maximum recharge depths using annual precipitation, and the resulting exceedance frequency distributions for the 1957–2003 period were plotted in Fig. 7 for the two treatments. The return periods for the maximum recharge depths of 1.5, 2, 2.5, and 3 m were 2.0, 3.1, 5.4, and 9.8 years for the sufficiently fertilized continuous wheat (intensive cropping), and 1.5, 1.9, 2.4, and 3.1 years for the unfertilized continuous wheat. For a given recharge depth, unfertilized wheat was more frequently recharged than sufficiently fertilized wheat, and the difference increased as the recharge depth increased. On average, soil water would be recharged beyond 3 m (i.e., completely eliminate the desiccated layer between 2 and 3 m) once in 9.8 years under the most intensive cropping of sufficiently fertilized continuous wheat and once in 3.1 years under less intensive cropping of unfertilized wheat.

The above results explain why desiccated (dry) soil layers formed and persisted over multiple years. The desiccated soil layer was defined as the soil layer that has the soil moisture ranging between the wilting point and a steady soil moisture level, normally less than 75% of field capacity (Li, 2001a). Many years of

field measurements showed that in the semiarid-subhumid climate at Changwu, a desiccated soil layer was rarely found in fields or years when grain yields were below average. However, desiccated soil layers often formed when grain yields were improved by increased fertilization and implementation of optimal management practices. For example, in the Changwu tableland region, after 13 years of continuous wheat cropping, the water storage in the high-yield fields was reduced by 270 mm compared to the low-yield fields (Li, 2001b). These field observations were consistent with the frequency analysis results, and therefore corroborated the conclusion of the frequency analysis.

The desiccated soil layer between 2 and 3 m would disappear and soil water storage within the 3-m depth would be fully recharged once in about 10 years under most intensive cropping, and much more frequently under other cropping systems in the region. This result should alleviate the concerns that the soil desiccation might be permanent and might have an irreversible effect on the sustainability of the current agricultural production systems in the region.

Nitrogen-enriched layers below the root zone were identified in adequately fertilized and intensively cropped fields in the region (Dang et al., 2003). The nitrogen leaching was affected by maximum recharge depth, frequency, and fertilization rate. Based on this study, deeper recharge depths in continuous fallow or unfertilized plots should not cause considerable downward movement of N because of low N concentration in the profiles. On the other hand, a shallower recharge depth and less frequent recharge would slow down N leaching in sufficiently fertilized plots. However, excessive N fertilization under intensive cropping is likely to cause considerable N leaching, especially in wet years.

#### Acknowledgements

This work was supported by the Knowledge Innovation Program of the Chinese Academy of Sciences (no. kzcx2-yw-424), Program for Changjiang Scholars and Innovative Research Team in University (no. IRT0749), and the National Key Technology R&D Program of China (no. 2006BAD09B09). The authors thank the

reviewers of this paper and the guest editors for their useful comments and suggestions.

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