available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/agwat

Comparison of measured and simulated water storage in dryland terraces of the Loess Plateau, China

Haishen Lü [a,b,*], Yonghua Zhu [a,b], Todd H. Skaggs [b], Zhongbo Yu [c]

[a] State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, College of Science, Hohai University, Naijing 210098, China
[b] U.S. Salinity Laboratory, 450 W. Big Springs Road, Riverside, CA 92507, USA
[c] Department of Geosciences, University of Nevada, Las Vegas, NV 89154, USA

ARTICLE INFO

Article history:
Received 5 March 2008
Accepted 31 August 2008
Published on line 9 October 2008

Keywords:
Computer models
Soil moisture
HYDRUS-2D
Terrace
Dryland agriculture
Conservation

ABSTRACT

In the hilly regions of China, developing sustainable agriculture requires implementing conservation management practices that prevent soil erosion and conserve soil and water resources. In the semiarid northwest Loess Plateau, the primary conservation management practice is terracing. Numerical simulation of soil water dynamics in terraces is potentially an efficient means of investigating the effects of terrace design on moisture retention, but little information is available on the accuracy of such simulations. In this work, we evaluated the accuracy of HYDRUS-2D simulations of water infiltration and redistribution in fallow, level, dryland terraces located in the Loess Plateau. The simulated soil water content distributions were in good agreement with experimental data. Modeling analyses showed that about one-third of the evaporative water losses occurred from the terrace riser surface. To prevent such losses, it is advisable to mulch the riser and minimize the riser surface area. The simulations also demonstrated that with other dimensions equal, wide terraces retain more water on a percentage basis than narrow ones due to a lower evaporating surface area are per unit volume of water storage. With other design considerations being equal, wide beds and minimal riser surface areas will likely enhance water capture and retention. Future analyses of terrace moisture dynamics may additionally include simulations of root water uptake, surface ponding, and runoff.

1. Introduction

China is a country of many mountains: approximately two-thirds of the country is mountainous. Developing sustainable agriculture in hilly terrain can be difficult. Consider, for example, the Loess Plateau, a 624,000 km^2 region in which 50% of the cultivated land is sloping. In some especially hilly areas, 70–90% of the cultivated land is sloping, with 15–20% having a slope greater than 25° (Wu et al., 2003; Jiao et al., 1999). Loess Plateau soils are highly erodible; past agricultural practices have contributed to widespread land degradation (Shi and Shao, 2000; Chen et al., 2007). Establishing sustainable agriculture in the Loess Plateau requires implementing management practices that limit soil erosion and conserve water and soil resources (Li, 2000). In the semiarid northwest Loess Plateau, the primary conservation management practice is terracing (Fig. 1), which increases rainfall infiltration and reduces erosion.

Terracing has been used in China for centuries, since the West-Han Dynasty (207 BC-25 AD) in foothills and valleys and since the South-Sung Dynasty (1127-1279 AD) in mountainous regions. The work of Li et al. (1994) provides

* Corresponding author at: College of Science, Hohai University, Nanjing 210098, China. Tel: +86 25-83786626.
E-mail address: Haishen2001@yahoo.com.cn (H. Lü).
0378-3774/$ – see front matter
doi:10.1016/j.agwat.2008.08.010

Fig. 1 – . Spring wheat growing on terraces in the Loess Plateau, China.

an illustrative example of the effectiveness of terracing. These authors investigated the conversion of sloping land to terraces in Taian City, Shandong Province and found that terracing had a significant impact on conservation: the development of narrow terraces on lands that sloped 5° and 10° reduced soil losses by 57.9 and 89.8% and nutrient losses by 89.3 and 95.9%, respectively. Additionally, soil bulk density was reduced by 4.0%, soil moisture increased by 20.7%, soil fertility increased by 42.4%, and yield increased by 22.4–37.3%.

Presently, terraces cover an area of about 13,200,000 ha in China (Wu et al., 2003). This land accounts for about 40% of the sloping land which could potentially be transformed into terraces (Wu et al., 2003). The recommended design for terraces (the riser height and slope, the bed width, etc.) is generally based on factors such as the slope of the land, the soil type and depth, and other parameters that affect erosion and slope stability (e.g. Shixiong et al., 2007). Typically such factors dictate an acceptable range of design parameters rather than an exact design. In dryland farming areas, it may be beneficial to additionally consider, within that acceptable range, the impact of design parameters on soil moisture retention and storage (e.g. Zhang et al., 2007). For example, one may consider the effect of terrace bed-width on root-zone water storage. Although this may be a secondary consideration, it is not inconsequential in many arid regions where water conservation is critically important.

Richards equation-based simulation of soil moisture dynamics within terraces is a relatively fast and inexpensive means of studying the effects of terrace design on root zone water storage and identifying optimal configurations. However, relatively little work has been done demonstrating the accuracy of such model simulations. In this work, we compared HYDRUS-2D (Šimůnek et al., 1999) simulations of terrace moisture dynamics with water distributions measured in two Loess Plateau terraces with differing bed widths. Additionally, we used model calculations to assess water losses and storage in the two terraces.

2. Materials and methods

2.1. *Study site description*

Field experiments were conducted at the Agricultural Experiment Station of Zhonglianchuan Village, Yuzhong County. The study area is located in the western part of the Loess Plateau (35°52′, 104°09′) at an altitude of approximately 1875 m. The climate is semiarid with mean annual precipitation of approximately 263 mm, nearly 70% of which falls between May and September. Mean annual temperature is 8.4 °C with a maximum of 20.7 °C (July) and a minimum of −9.1 °C (January). Average annual potential evaporation is 1786 mm. The soil is a sandy loam of loess origin (Haplic Orthic Aridisol). The depth to groundwater is large (>120 m).

2.2. *Experimental design*

In the study area, terraced agriculture accounts for approximately 43% of land use. The widths of the terraces are generally in the range of 2–15 m. Some of the terraces are planted as orchards, while others are planted with annual crops (e.g. wheat, corn). Two terraces were selected that differed in bed width. Terrace 1 was narrow, with a bed width of 2 m, a vertical height of 1.8 m, and a riser slope of 70°. Terrace 2 was wider, with a bed width of 4 m, a vertical height of 2.6 m, and a riser slope of 69°. The terraces both faced southeast and were fallow during the year of the study.

The study started on April 1, 2004 and ended on May, 1, 2004. During this time, rainfall occurred only on April 2, when 34 mm fell over a period of 9.3 h, as measured by a 20 cm diameter cylindrical rain gauge. A small berm on the edge of

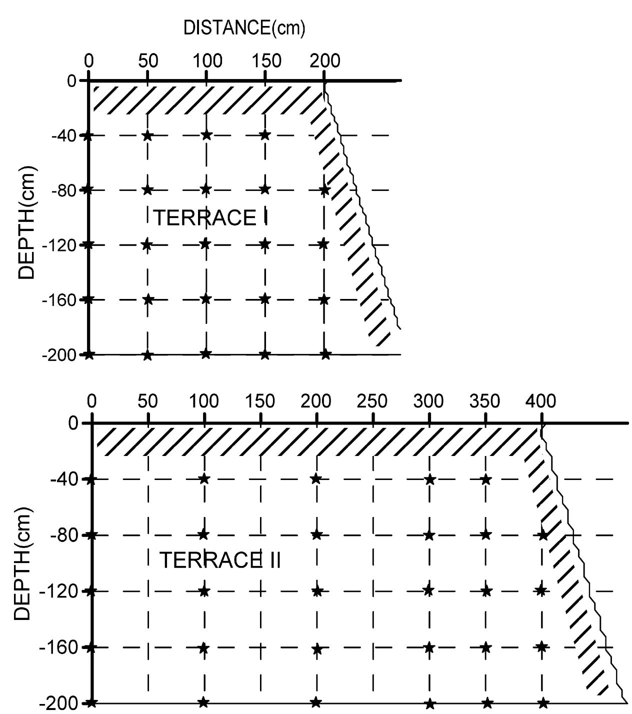

Fig. 2 – Vertical profiles of the two terraces. The locations of moisture content measurements are indicated by stars. The diagonal hash marks indicate the soil surface.

Table 1 – Soil characteristics of the experimental terraces

Terrace	Depth (cm)	Bulk density (g cm^{-3})	Clay (%)	Silt (%)	Sand (%)
I	18–22	1.16	33	49	18
	38–42	1.18	32	49	19
	58–62	1.14	35	50	15
	Average	1.16	33	49	17
II	18–22	1.03	36	54	10
	38–42	1.19	32	46	22
	58–62	1.13	30	48	22
	Average	1.12	33	49	18

the terrace insured that runoff did not occur from the bed surface.

As shown in Fig. 2, a coordinate system for each terrace was established in the vertical plane with the origin at the inner edge of the terrace surface. Also shown in Fig. 2 are the locations and depths of soil moisture measurements made on April 1, April 3, April 13 and May 1. Measurements were obtained by extracting a 200 cm long core at each sampling location; from this core, three 30–50 g replicate soil samples were taken for each of depths indicated in Fig. 2. The water content of each sample was determined gravimetrically: samples were weighed as collected, dried at 105 °C, and then re-weighed to determine soil moisture.

Measurements of additional soil physical properties included the determination of soil bulk density and percentage sand, silt, and clay for the depths 18–22, 38–42, and 58–62 cm. The measured values for these physical properties are presented in Table 1.

2.3. *Numerical modeling*

To study soil moisture in terraces with different bed widths and investigate the impact of riser (side-slope) evaporation, we used HYDRUS-2D (Šimůnek et al., 1999) to simulate water infiltration and redistribution in two trapezoidal profiles based on those shown (Fig. 2). Assuming a homogeneous and isotropic soil, the governing equation for water flow is the 2D Richards equation

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}\left(K(h)\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial z}\left(K(h)\frac{\partial h}{\partial z} + K(h)\right) \quad (1)$$

where θ is the volumetric water content ($cm^3\,cm^{-3}$), h is the soil water pressure head (cm), t is the time (day), x is the horizontal space coordinate (cm), z is the vertical space coordinate (cm) and K is the hydraulic conductivity (cm day^{-1}). The soil hydraulic properties were specified according to the van Genuchten model

$$\theta(h) = \begin{cases} \theta_r + \dfrac{(\theta_s - \theta_r)}{(1+|\alpha h|^n)^m}, & h<0 \\ \theta_s, & h \geq 0 \end{cases} \quad (2)$$

$$K(h) = \begin{cases} K_s S_e{}^l[1-(1-S_e{}^{1/m})^m]^2, & h<0 \\ K_s, & h\geq 0 \end{cases} \quad (3)$$

where

$$S_e = \frac{\theta-\theta_r}{\theta_s-\theta_r}, \quad m = 1-\frac{1}{n}$$

and where θ_s is the saturated water content ($cm^3\,cm^{-3}$), θ_r is the residual water content ($cm^3\,cm^{-3}$), K_s is the saturated hydraulic conductivity (cm day^{-1}) and α, n, and l are the shape parameters. HYDRUS-2D uses the finite element method to solve Eqs. (1)–(3).

As noted above, runoff from the level beds was negligible. For the simulations, the bed surface boundary condition during the rainfall event was set to a constant water flux, equal to the total precipitation divided by the duration of the rainfall. Infiltration on the riser surface during rainfall was significantly smaller, and as a first approximation we assumed in the simulations that it was zero (100% run-off). Additionally, we ignored any water that may have been introduced to the bed surface by runoff from an up-slope riser. This latter assumption contradicts the assumption of 100% run-off from the simulated riser surface and likely causes the simulated infiltration at the bed surface to be lower than what actually occurred in the field. Unfortunately, no information was available about the geometry or design of the uphill terrace, so it was not possible to quantify or justify an estimate of the up-slope runoff.

For all other times, the bed and riser surfaces were treated as "atmospheric" boundaries (Šimůnek et al., 1999), meaning that within HYDRUS-2D an evaporative flux was prescribed when the water pressure head at the soil surface was above a threshold value of h_{crit} (=−10,000 cm), whereas a constant pressure head equal to h_{crit} was prescribed otherwise. With this boundary condition, water evaporates from the soil at the potential rate when the surface is wetter than the threshold value, and at a lower rate (which is calculated based on soil conditions) when the soil dries to the threshold wetness. A value for the daily potential evaporative flux was calculated from weather station data using the FAO-56 Penman–Monteith equation (Allen et al., 1998). The distance between the site and the weather stations was 55 km. The values of the parameters in Penman–Monteith equation came from Wu et al. (2005).

Throughout the simulation, the left (inner) vertical boundary of the terrace profile (Fig. 2) was specified as a zero-flux condition. It is possible that a zero-flux condition did not exist in the field for the entire duration of the study, but lacking data on the boundary, we implemented the zero-flux condition as a first approximation. The bottom boundary was specified as a

Table 2 – Estimated soil hydraulic parameters

Terrace	θ_s ($cm^3\,cm^{-3}$)	θ_r ($cm^3\,cm^{-3}$)	K_s (cm h^{-1})	α (cm^{-1})	n	l
I	0.43	0.078	1.04	0.036	1.56	0.5
II	0.52	0.092	1.98	0.0091	1.50	0.5

free drainage condition (pressure head gradient equal to zero); the deep water table was thus assumed to have no impact on the terrace moisture dynamics.

Running HYDRUS-2D required specifying the hydraulic parameters θ_s, θ_r, K_s, α, n and l, as well as the initial water content distribution. We estimated the hydraulic parameters using the ROSETTA pedotransfer model (Schaap et al., 2001) that is included in the HYDRUS software package. ROSETTA is a neural network-based model that predicts hydraulic parameters from soil texture and related data. We input into ROSETTA the profile average values for the soil separates and bulk density that are given in Table 1, and obtained the estimated parameters that are given in Table 2.

Initial water content profiles for the terraces on April 1 were developed in a two-step process. First, for each terrace, a water content profile was created by assuming that at each point in the soil the water content was equal to the water content of the nearest measurement made on April 1 (measurement locations shown in Fig. 2). This created moisture profiles with a patchwork-like pattern. To obtain more realistic moisture distributions, these initial conditions were input into HYDRUS-2D and allowed to evolve for two simulated days with a constant surface potential evaporation rate of 3.7 mm h^{-1} (typical value for the days leading up to April 1). The resulting water content profiles (shown in Fig. 3) were then used as the April 1 initial conditions.

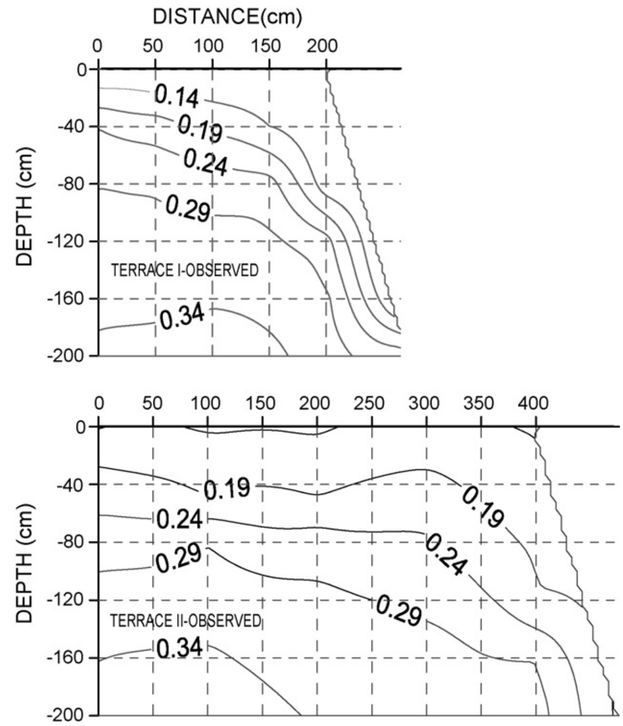

Fig. 3 – The initial volumetric water content distribution for Terraces 1 and 2 on April 1, 2004.

3. Results and discussion

Figs. 4–6 show for both terraces the measured and simulated volumetric water content distributions for April 3, April 13, and May 1. The contours in these plots were drawn using a Kriging interpolation algorithm. Because the measured data were relatively sparse, some of the contour details in the "observed" plots may lack significance. Nevertheless, the plots in Figs. 4–6 demonstrate that overall

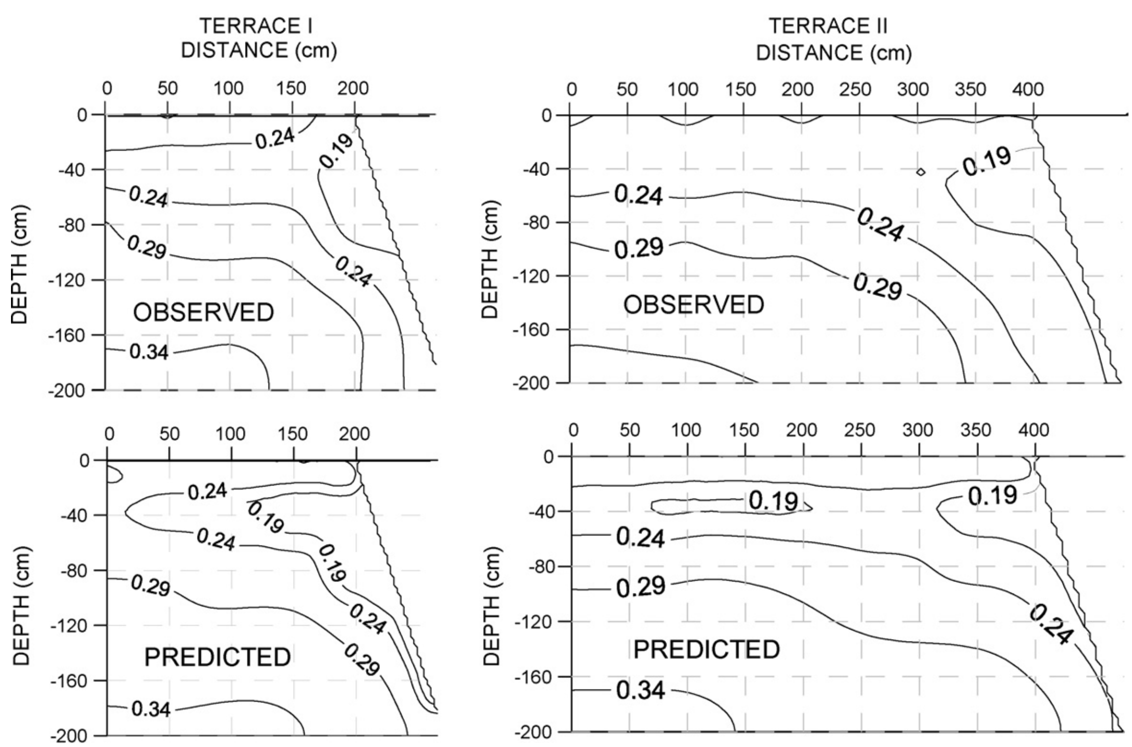

Fig. 4 – Observed and predicted volumetric water contents for April 3, 2004.

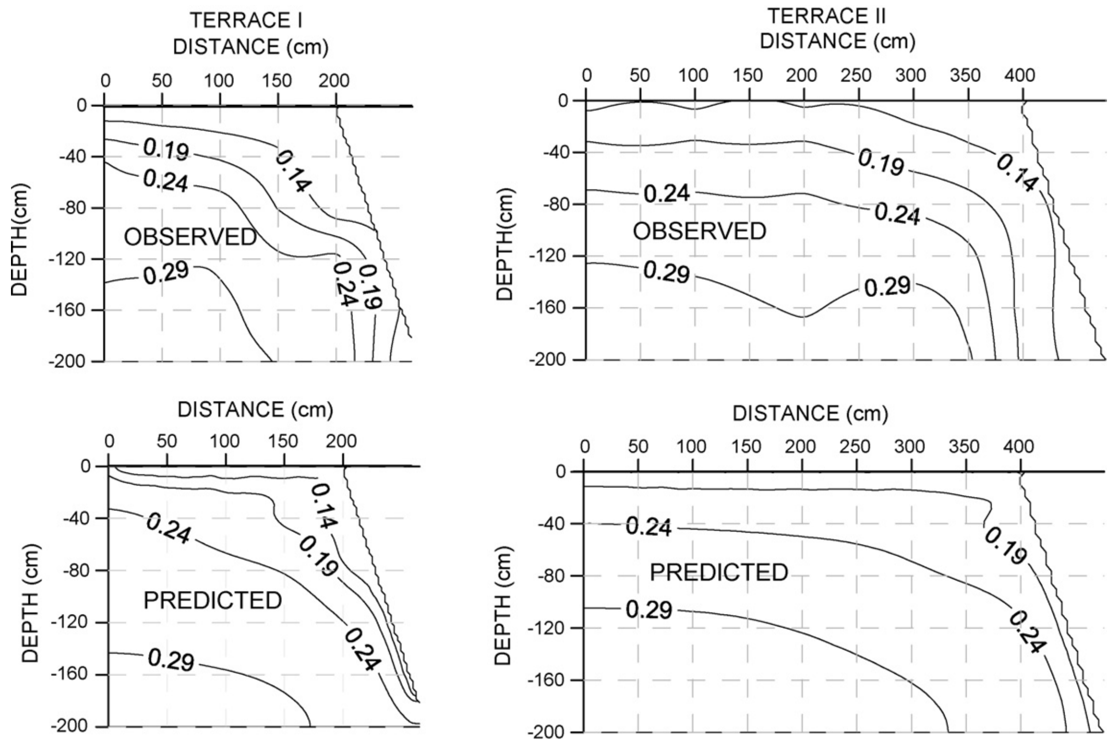

Fig. 5 – Observed and predicted volumetric water contents for April 13, 2004.

the predicted distributions of soil water are in agreement with the data.

Fig. 7 contains plots showing measured and simulated water contents along selected vertical transects. These plots permit a more precise visual comparison of data and model predictions than do the contour plots. Additionally, the root-mean-square-error (RMSE) computed from these plots (Table 3) provides a quantitative measure of the goodness-of-fit at various locations across the profile. As indicated in Table 3, the RMSE ($cm^3\ cm^{-3}$) was in general largest near the

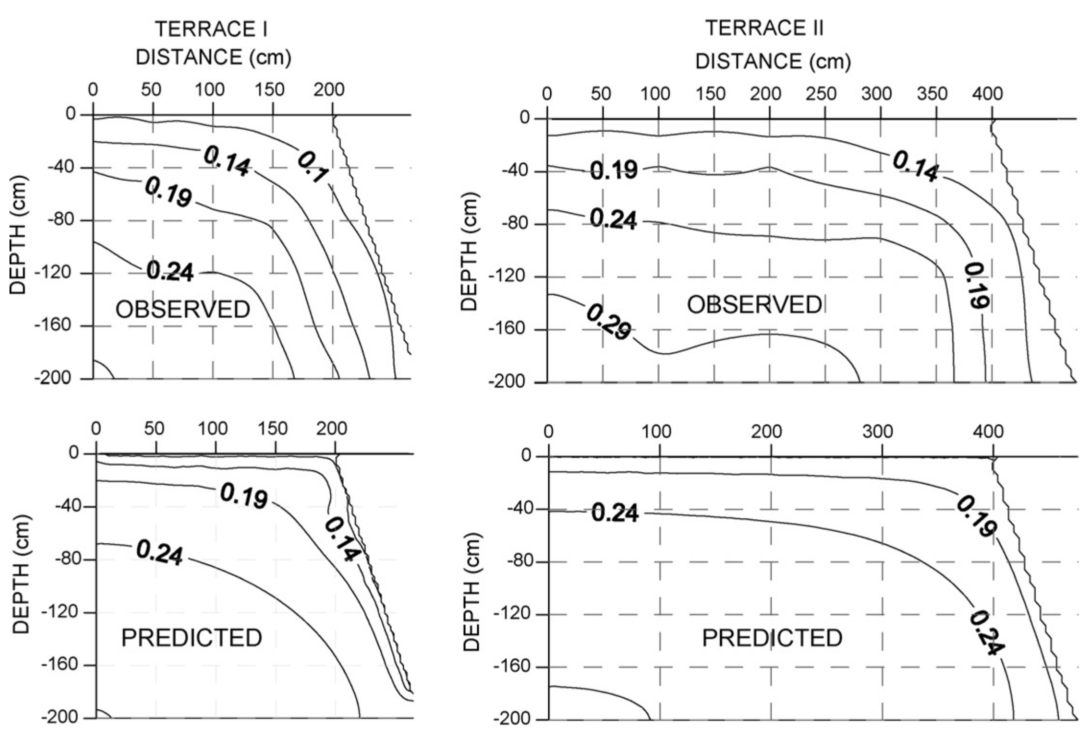

Fig. 6 – Observed and predicted volumetric water contents for May 1, 2004.

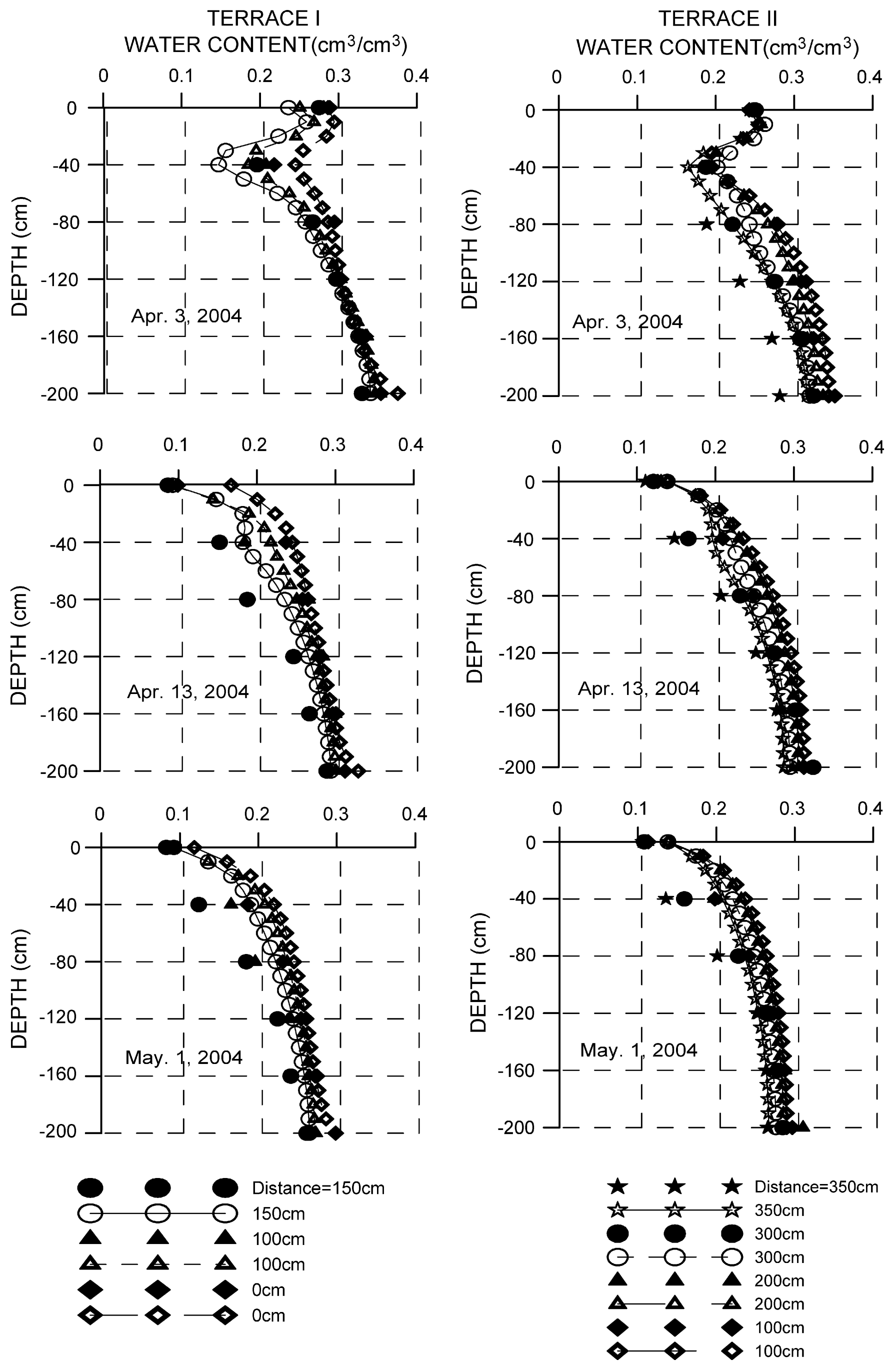

Fig. 7 – Comparison of measured and predicted water contents profiles for selected dates and locations on the terrace beds. Closed symbols are measured data, open symbols with lines are model predictions.

outer edges of the terraces (as high as 0.068) and was smallest closer to the inner edges (generally less than 0.03). Overall, the predictions depicted in Figs. 4–7 are good, particularly considering that the simulations were done without any fitting to the water content data, and without characterizing in detail the soil hydraulic properties of each terrace. Overall, we judge the simulations to be sufficiently accurate to warrant the future use of HYDRUS-2D to investigate the impacts of terrace design on soil moisture dynamics and water retention. We note also that HYDRUS-2D has capabilities for simulating root growth and root water extraction, and may be coupled with an overland flow model to account for runoff.

At present, we can make the following observations about moisture dynamics in the two terraces, based on the measured data and modeling results. The 34 mm of rain on April 2 infiltrated rapidly and quickly changed the water content profile to a depth of 40 cm (Figs. 3 and 4). Below this depth, the water content distribution remained relatively constant throughout the study. After the rainfall, the surface soil began drying rapidly due to a large potential evaporation. Figs. 5 and

Table 3 – RMSE ($cm^3\ cm^{-3}$) ($\times 10^2$) for water content profiles predicted with HYDRUS-2D

Date	Position on terrace cross-section							
	0 cm	50 cm	100 cm	150 cm	200 cm	300 cm	350 cm	400 cm
Terrace I								
April 3	1.49	1.89	1.60	6.53	2.48	–	–	–
April 13	2.90	0.98	1.60	2.55	5.46	–	–	–
May 1	1.83	2.37	2.50	3.32	5.53	–	–	–
Terrace II								
April 3	0.59	–	0.79	–	0.51	1.09	2.99	4.51
April 13	1.80	–	1.72	–	1.63	2.75	2.64	6.79
May 1	2.18	–	2.16	–	2.42	2.95	3.53	6.10

Table 4 – Terrace water storage, 0–200 cm

Date	Position on terrace cross-section							
	0 cm	50 cm	100 cm	150 cm	200 cm	300 cm	350 cm	400 cm
Terrace I								
April 3	63.2	60.9	59.2	56.7	47.1	–	–	–
April 13	56.2	53.3	52.1	49.6	48.1	–	–	–
May 1	50.8	50.0	48.4	46.2	37.6	–	–	–
Terrace II								
April 3	60.6	–	60.1	–	58.3	56.1	53.2	49.3
April 13	57.0	–	56.5	–	55.2	52.8	50.4	46.1
May 1	54.3	–	54.1	–	53.1	51.1	49.0	44.2

All the values are in cm.

6 give an indication of the impact of evaporation from the riser surface, with the right edge of the profile losing water over time. As time progressed, evaporation slowed as the increasingly dry surface became a barrier to liquid water flow. Table 4 lists the quantity of water stored in the terrace profiles at various times and locations across the beds, and again the loss of water along the riser boundary is evident. In both terraces, model calculations indicated that about one-third of the water lost to evaporation exited the profile through the riser surface. This large water loss is consistent with the field observations of Zhao et al. (2005), who found significantly lower water content in narrow terrace beds near the riser edge than near the inner edge, especially in months when precipitation was low.

The simulation results also showed that the wider terrace retained a higher percentage of its water than the smaller one. Specifically, over the 28 days immediately following the April 2 precipitation, the larger terrace retained 90% of its water while the smaller terrace retained 81%. This result can be understood by noting that the ratio of the length the evaporating surface to the cross-sectional area of a terrace decreases if the bed length is increased (with all other dimensions constant). For example, a hypothetical terrace similar to that shown in Fig. 2 with a vertical height of 2 m, a riser slope of 70°, and a bed width of 2 m has an evaporating surface length (bed surface + riser surface) equal to 4.13 m, a cross-sectional area equal to 4.73 m^2, and thus a ratio equal to 0.87 m^{-1}. The same terrace with a bed width of 4 m has an evaporating surface length equal to 6.13 m, an area equal to 8.73 m, and a ratio equal to 0.70 m^{-1}. Hence, with all other considerations equal, a wider bed means there is less evaporating surface length per unit area of water storage (or, for the full 3D terrace, less evaporating surface area per unit volume of storage).

4. Conclusions

Terrace design is generally dictated by the slope of the land, the soil type and depth, and related factors that affect erosion and slope stability. For example, flat slopes favor wide terraces and low risers, while steep slopes favor narrow terraces and high risers. However, these primary factors typically dictate not an exact design but rather a range of acceptable design parameters, and within that range it may be possible to consider additional factors such as the effect of terrace design on water retention and storage. These may be secondary considerations, but they are not inconsequential in areas such as the Loess Plateau, where water scarcity makes conservation extremely important. Numerical modeling of water dynamics in terraces is potentially a cost-effective way of investigating the effect of terrace design on water conservation.

In this work, we evaluated the accuracy of HYDRUS-2D simulations of water infiltration and redistribution in level, dryland terraces. The soil water content distributions predicted with HYDRUS-2D were found to be in good agreement with experimental data. The results provide support for using HYDRUS-2D in future investigations of the effects of terrace design and management on water capture and retention. Our work examined fallow terraces without surface water ponding or runoff. Simulations for more general conditions will require implementing the root growth and water uptake routines in HYDRUS, as well as coupling HYDRUS with an overland flow model. The ROSETTA pedotransfer model included in HYDRUS was an effective tool for estimating the soil hydraulic parameters that are needed for the simulations. In future investigations, ROSETTA will be especially useful for studying the effects of different soil textures on terrace performance.

Our modeling analysis of two Loess Plateau level terraces found that about one-third of the evaporative water losses occurred across the riser surface. To prevent such losses, it is advisable to mulch the riser, and perhaps design the terrace so as to minimize the riser surface area. In comparing simulation results for narrow and wide terraces, we noted that with all other dimensions equal, terraces with wide beds have less evaporating surface per volume of water storage and thus retain a higher percentage of their stored water. Thus, wide beds and minimal riser surface areas will likely enhance water capture and retention.

Acknowledgements

This research was supported by the National Key Basic Research Program of China (2006CB400502) and the Jiangsu Planned Projects for Postdoctoral Research Funds. Additional support was provided by the Program for Changjiang Scholars and Innovative Research Team in University (PCSIRT) through the project "Study on Coupled Processes of Atmosphere-Land-Hydrology" (IRT0717).

REFERENCES

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration: guidelines for computing crop requirements. Irrigation and Drainage Paper No. 56. FAO, Rome, Italy, 300 pp.

Chen, L., Wei, W., Fu, B., Lü, Y., 2007. Soil and water conservation on the Loess Plateau in China: review and perspective. Progress in Physical Geography 31, 389–403.

Jiao, J., Wang, W., Li, J., 1999. Analysis of soil and water conservation benefits derived from level terracing under different rainfall conditions in a hilly loess region. Journal of Soil Water Conservation 3, 60–64 (in Chinese).

Li, X.Y., 2000. Soil and water conservation in arid and semiarid areas: the Chinese experience. Annals of Arid Zone 39, 377–393.

Li, H., Wei, Y., Fang, J., Lu, X., 1994. Effects of converting hillsides to terraces in the rotten granite shale region. Soil and Water Conservation in China 7, 18–21 (in Chinese).

Schaap, M.G., Leig, F.J., van Genuchten, M.Th., 2001. ROSETTA: a computer program for estimating soil hydraulic properties with hierarchical pedotransfer functions. Journal of Hydrology 251, 163–176.

Shi, H., Shao, M., 2000. Soil and water loss from the Loess Plateau in China. Journal of Arid Environments 45, 9–20.

Shixiong, C., Chen, L., Feng, Q., Liu, Z., 2007. Soft-rister bench terrace for the hilly loess region of Shaanxi Province, China. Landscape and Urban Planning 80, 184–191.

Šimůnek, J., Sejna, M., van Genuchten, M.Th., 1999. The HYDRUS-2D software package for simulating the two-dimensional movement of water, heat, and multiple solutes in variable-saturated media. IGWMC-TPS 53, Version 2.0. International Ground Water Modeling Center, Colorado School of Mines, Golden, CO.

Wu, F., Zhang, Y., She, D., Song, J., 2003. Preliminary study on the environmental effects of level terracing in the Southern Loess Plateau. Soil and Water Conversation Research 10, 128–130 (in Chinese).

Wu, S., Yin, Y., Zheng, D., Yang, Q., 2005. Climate change in the Tibetan plateau during the last three decades. Science in China (Series D, Earth Sciences) 35, 276–283 (in Chinese).