黄土高原典型小流域综合治理的水文生态效应

杨开宝[1]，刘国彬[1,2]，吴发启[1]，孙宝胜[1,*]

（1. 西北农林科技大学资源环境学院，陕西 杨陵　712100；2. 中国科学院水利部水土保持研究所，陕西 杨陵　712100）

摘要：从流域产流规律及水土保持措施改变引起的土壤水分状况和流域蒸散发的变化等方面评价了黄土丘陵沟壑区泉家沟流域水土保持措施变化对流域水分生态环境的影响。结果表明：水土保持与生态建设过程改变了土地利用结构，对小流域水环境变迁具有很大的影响作用，主要表现在：减少地表径流量，径流模数 1996 ~ 2000 年平均较 1980 ~ 1985 年减少了 36.1%；不同治理措施土壤水分状况不同，灌木林地、人工草地和乔木林地均存在深度和厚度不等的土壤"干层"；不同地貌部位土壤储水差异很大，阴坡的水分环境优于阳坡，沟底优于峁顶，缓坡优于陡坡；林草措施对流域总蒸散量起着决定性作用，1991 ~ 1995 年流域林草地面积达到最大，总蒸散量也达到最大，与治理初期相比，总蒸散量累计增加了 56.3 mm。

关键词：黄土丘陵沟壑区；小流域；生态建设；水环境

文章编号：1000-0933(2008)05-2042-10　**中图分类号**：P343，P941.74，Q146　**文献标识码**：A

Hydrological and environmental responses to comprehensive control of soil loss in a typical watershed of hill and gully region of the Loess Plateau

YANG Kai-Bao[1], LIU Guo-Bin[1,2], WU Fa-Qi[1], SUN Bao-Sheng[1,*]

1 *College of Resource and Environmental Sciences, Northwest A & F University, Yangling, Shaanxi* 712100, *China*

2 *Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling, Shaanxi* 712100, *China*

***Acta Ecologica Sinica*, 2008, 28(5): 2042 ~ 2051.**

Abstract: Certain aspects of hydrological and environmental response to conservation practices and land use pattern changes in the Quanjiagou watershed in the hilly and gully loess area were assessed, such as runoff, dynamics of soil moisture and evaportranspiration. The results showed that soil-water conservation practices and ecological construction had significant influence on the hydrological and environmental processes of the watershed. Surface runoff was decreased by 36.1% from 1980 to 2000. Soil moisture status varied greatly with different erosion control practices: shrub land, grassland and timber forestland all had "dry layer" in the soil profile with different thicknesses and depths. There existed great differences in soil water storages with different landform position. The north-facing slopes had better hydrological environment in the soil than the south-facing slopes, and gully bottoms were better than hilltops and gentle slopes, better than steep slopes. Forest and

基金项目：国家"十五"科技攻关课题资助项目（2001BA508B17）；陕西省自然科学基金资助项目（20020201102）；西北农林科技大学科研专项资助项目（05ZR031）

收稿日期：2007-02-02；**修订日期**：2007-12-29

作者简介：杨开宝（1964 ~ ），男，陕西横山县人，博士生，副研究员，主要从事黄土高原自然降水高效利用和水土保持研究. E-mail: yangkaibao@tom.com

* 通讯作者 Corresponding author. E-mail: sunbs1958@sohu.com

Foundation item: The project was financially supported by the 10th 5-year plan for tackling key scientific and technological subjects (No. 2001BA508B17); Shaanxi Provincial Natural Science Fund (No. 20020201102); the Special Scientific Research Projiect of Northwest A&F university (No. 05ZR031)

Received date: 2007-02-02; **Accepted date**: 2007-12-29

Biography: YANG Kai-Bao, Ph. D. candidate, Associate professor, mainly engaged in efficient use of natural precipitation of small watershed and ecological construction on the Loess Plateau. E-mail: yangkaibao@tom.com

grass practices played a decisive role in evapotranspiration. The total evapotranspiration reached a maximum in 1991 — 1995, and cumulative evapotranspiration increased by 56.3mm compared to the start of erosion control.

Key Words: hilly and gully loess area; watershed; ecological construction; hydrological and environmental responses

Serious soil erosion on the Loess Plateau has resulted in a series of environmental problems and attracted worldwide attention. In the decades following the founding of new China, officials at all levels of government have expressed the importance of erosion control on the Loess Plateau. A great deal of research has been conducted and some successful control examples have emerged. The state listed comprehensive erosion control of the loess plateau as the key project " regional comprehensive control trial" in 1986 — 1990, and specific experimental areas were set up in the Hill and Gully region of the Loess Plateau. Research work was conducted surrounding the key issues of soil erosion, drought and the worsening cycle of eco-economy. A wealth of experience concerning erosion control was obtained through this project and a great deal of benefits were produced as well[1,2]. However, the controlling models based on the bio-engineering practices against soil erosion have brought about a series of hydrological and environmental problems[3,4]. Regarding a small watershed, water cycling was greatly enhanced, and may lead to changes in the hydrological cycle and transfer path with the increasing of control degree of water-soil conservation, vegetation cover and the productivity of farmland[5,6]. Meanwhile, the " dry layer" in soil profile appeared widespread in the Loess Plateau, which resulted in larger fluctuations of crop yield and apple output, vegetation degradation and even death, furthermore affecting the rehabilitation and reconstruction of vegetation in small watersheds[7-10]. In recent years, experts and scholars have conducted a lot of research on the hydrological and environmental responses to erosion control practices in small watersheds[11-13]. However, most of the research focused on the response of individual erosion control practice on the hydro-environment. By dissecting the nearly 20-year process of soil-water conservation and ecological reconstruction of a typical small watershed, Quanjiagou gully, the writers evaluated the response of the integrated control practices on soil moisture conditions and hydro-environment of the small watershed in the hilly and gully areas of the Loess Plateau based on the analyses of runoff rules, soil moisture status with different land use pattern and evapotranspiration in the valley, etc. The purpose of the study was to supply the theoretical guideline for rational use of land resources and improving the eco-environment of the small watersheds in the hilly and gully loess areas.

1 Study site and methods

1.1 Study site

The study site was the Quanjiagou watershed, which is located in Mizhi County, Shaanxi Province. The watershed is part of the first sub-region of the Loess Plateau —— hilly and gully area. The area of the watershed is 5.19 km^2. The main gully in the watershed is 4.13 km long and a second-class tributary of the Wuding River. The region has a semi-arid, temperate, continental monsoon climate. The mean annual temperature is 8.4℃ and the mean annual precipitation is 425 mm. Over 70% of the annual precipitation is received between June and September. Loess and paleosol is the predominant soil type in the region, with a deep and thick soil profile of 50 — 100m, and loose and homogeneous soil texture. The soil has superior water infiltration and retention capacity. Agricultural production is mostly dependent on natural rainfall. Main crops are millet, soybean, potato and corn. The man-made vegetation includes caragana, poplar, black locust, and alfalfa.

Studies on soil-water conservation and integrated control of Quanjiagou watershed began in 1980. The focus of these studies was the rational utilization of land resources. The Guanjiagou watershed was listed as one of the state experimental and pilot areas for comprehensive erosion control on the Loess Plateau from 1986 to 2000. The overall objective was to create a reasonable eco-system with an improved cycle and efficient agricultural production to ensure the stability and development of the ecological system. From 1981 to 2000, the course of the Quanjiagou comprehensive erosion control experimental area can be roughly divided into three stages: the first stage, during 1980 — 1985, was the stage of land use structure adjustment centered on the rational utilization of land resources, and the main practice was implemented of withdrawing farmlands to plant trees and grasses; the second stage was during 1986 — 1990 to advance the adjustment of industrial structures focused on the development of artificial grassland and animal husbandry. Main practices adopted were the construction of basic stable farmlands and raising crop yields, and also developing livestock; the third stage was from 1991 to 2000, principally for the consolidation of the achievements obtained during the early stages and the speeding up of economic development. The key measures implemented were development of scaled livestock raising and tree crops, and popularisation of agricultural and practical techniques for high yields. For the results of comprehensive erosion control, land use pattern of farmland, forestland and grassland was adjusted from 14.8:3.8:1 in 1979 to 1.4:1.3:1 in 1990. Engineering measures used for soil and water conservation were basically terminated during 1991 —1995 and 1996 —2000 while biological measures predominated for comprehensive erosion control of the watershed. Thus vegetation cover was further increased, and the area of fruit trees enlarged. By the end of 2000, forest and grass cover reached 49.2% in the experimental and pilot area with a control degree of 73.5%, increased by 31.1 and 41.8 percent respectively compared to the year 1979. Soil and water loss had basically been brought under control, and the ecological environment was continuing along the trend of upgrading development.

1.2 Methods

Runoff quantity from the watershed in its natural state was calculated with an empirical formula[14] established from a single rainfall event in the watershed. Runoff discharge was monitored at the mouth of the gully with an open channel flow measurement facility. Automatic rainfall recorders were used for the long-term monitoring of precipitation at multiple points within the watershed. Eight land use types were determined based on field investigations in the watershed: slope farmland, terraced land, dam land, grassland, orchard, forestland, shrubland and non-productive land. A 1:5000 land use map for the year 2000 was used to select 32 representative sampling points on both sides of the gully. There were four sampling points for each of the eight land use types. Soil samples were collected with a soil corer on April 15 —20, 2003 and April 17 —22, 2004. Samples were collected in 20 cm increments from the soil surface to a depth of 10 m. The soil moisture content was determined by oven-drying the samples at 105℃ until the weight was constant. In addition, a ring knife was used to collect samples in 20 cm increments from the soil surface to a depth of 1 m for the determination of soil bulk density. The soil moisture content was used to estimate soil water storage in the watershed.

2 Results

2.1 Runoff and its Characteristics

Runoff and its characteristics depend on rainfall and the underlying horizon conditions in the watershed. If the nature of the underlying horizon changes, runoff characteristics will be influenced accordingly. Fig. 1 illustrates the runoff process in which rainstorms took place on August 19, 2001 and August 15, 1982 respectively. Rainfall was 53.0mm and 52.3mm, and lasted for 126 minutes and 120 minutes respectively. The two curves in Fig. 1 indicate the runoff characteristics at the beginning and end of erosion control respectively. It was clear that the process of runoff convergence went up sharply with a single asymmetry peak at the early stage of erosion control in the small watershed. Compared to the process of runoff convergence at the end of control implementation in 2001, it lasted longer with a greater flooding peak discharge, and freshet went up fast and down slowly, this being the over-infiltration characteristic of runoff. As to the small watershed controlled by integrated practices, the process of runoff convergence was significantly shortened with a smooth flooding peak. Freshet up- and down-lines were basically symmetrical.

According to findings by the Suide Water Conservation Station of Huanghe Water Conservancy Committee, the first sub-region of the Loess Plateau, the hilly and gully loess area, is mostly one of over-infiltration runoff. It was considered that rainfall (P), rainfall intensity (I) and the early-influenced rainfall (P_a) were the major factors in the determination of runoff quantity. Hereby runoff empirical formula was established for a single rainfall of small watersheds[14], as follows:

$$R = 3.567(P + P_a)^{1.29} I^{1.19} \qquad Pa = P/I^{0.5} \tag{1}$$

In the formula, R = runoff of a watershed with a single rainfall ($m^3 \cdot km^{-2}$); P = single rainfall (mm); I = rainfall intensity (mm h^{-1}); $Pa = P/I^{0.5}$, early-influenced rainfall. The empirical formula was used to calculate annual runoff for Quanjiagou watershed, and the calculated values were compared with the monitored values at the gate of the gully. The results (Fig. 2) showed that the calculated values were coincident with the monitored values. The maximum runoff occurred in 1987, and after that the annual runoff coefficient (runoff per mm rainfall) showed a clearly decreasing trend.

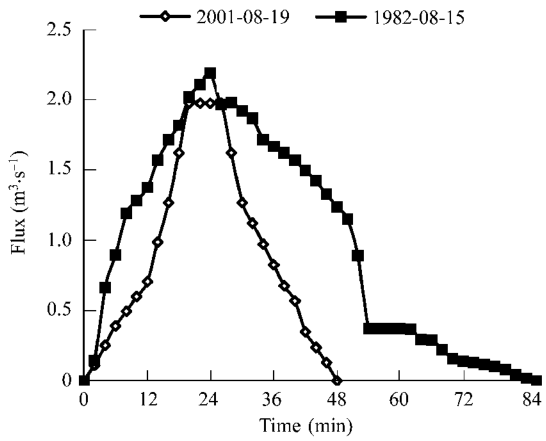

Fig. 1 Process of runoff in Quanjiagou watershed

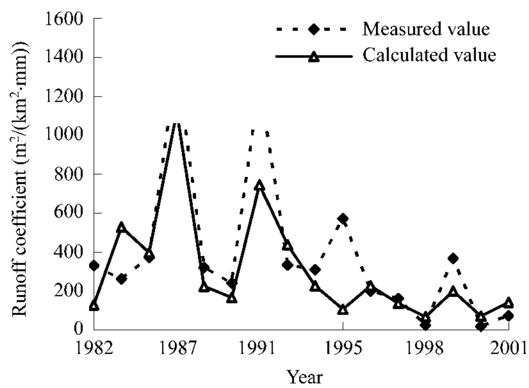

Fig. 2 Chang of runoff coefficient in Quanjiagou wareshed

2.2 Impact of Land Use Structure on Runoff

Statistical information from the Quanjiagou experimental area showed that the land use pattern changed with the following features: (1) slope farmland and non-productive land decreased obviously while terraced land and forest and grass land increased greatly; (2) forest and grass cover was raised from 14.65% in 1979 to 25.34% in 2001 in the watershed; (3) land use pattern gradually tended to be rational, with the farmland-woodland-grassland ratio being adjusted from 14.8:3.8:1 at the beginning of erosion control to 1.4:1.3:1 in 1990. After 1990, depression in the livestock raising industry resulted in the decrease of grassland owing to market problems: however economic forests, mainly apple trees, increased rapidly, therefore still maintaining the increasing trend of the total area of forest and grass land. A great increase in orchard area resulted in some terraces and slope farmland being converted into woodland. Meanwhile the area of woodland increased substantially with the withdrawal of slope farmland for forest and vegetation reconstruction. This meant that hillside farmland, grassland and land difficult to use decreased accordingly, and forest cover rate increased. By the end of 2001, slope farmland had decreased by 39.1%, and grassland and woodland increased by 196.6% and 165.7%, respectively. Furthermore orchard area increased by 3 times. Control degree, the percentage of the total area of erosion control practices implemented, including terraced land, dam land, woodland and grassland, compared to the area of productive land in the watershed, increased from 48.9% in 1982 to 73.7% in 2000.

The changes of land use pattern in a small watershed will certainly affect the nature of underlying horizon, and result in a change of runoff and convergence features in the watershed. Fig. 3 indicates the relation between runoff coefficient and the evolutionary process of constructing basic farmland (terraced land and dam land) and planting trees and grasses on the withdrawn slope farmlands from 1981 to 2000. During 1980 — 1985, the area of basic farmland, forestland and grassland was increased by the rational adjustment of land use pattern in the experimental area. Biological practices combined with engineering ones were implemented for water and soil conservation during 1980 — 1985, and benefits were being produced by the 1986 — 1990. Runoff decreased to a large extent in the experimental area as the area of forest and grass increased rapidly on the withdrawn slope farmlands. Runoff coefficient declined from 242.3 $m^3/(km^2 \cdot mm)$ averaged during 1980 — 1985 to 154.8 $m^3/(km^2 \cdot mm)$ averaged during 1996 — 2000, a decrease of 36.1%. Reduction of land surface runoff indicated that its function was strengthened by soil and water conservation practices, while hydrological environment was dried on the other hand.

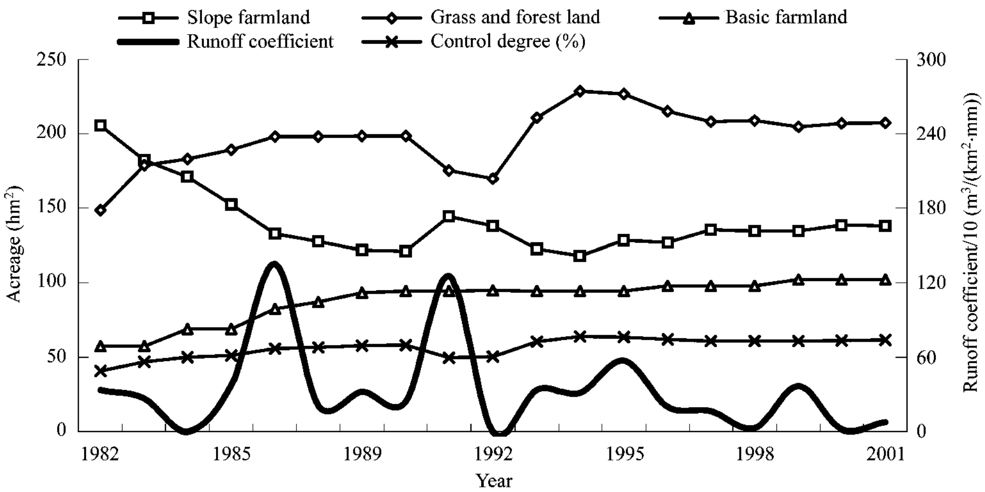

Fig. 3 Basic farmland includes treeaced land and dam land

Control degree is the percentage of the total area of conservative practices implemented, including dam land, treeaced land, grassland and woodland, compared to the total productive land area in the watershed

However, rainfall was up to 447.6mm during the flood season in 1987, and runoff occurred twice. Rainfall that brought about runoff was 100.6 mm and averaged 50.3 mm each time, the largest in recent years. So runoff coefficient was greatest, up to 1351.7 $m^3/(km^2 \cdot mm)$, in recent years. The experimental area suffered the most serious rainstorm of once every 50 years on June 7, 1991. It received 47.3 mm of rainfall within 17 minutes. Runoff discharge was up to 25 m^3/s. at the highest flood peak at the mouth of the gully, and runoff coefficient reached 1253.9 $m^3/(km^2 \cdot mm)$. This means that we still have a long way to go to control water and soil loss in the Loess Plateau.

2.3 Soil Moisture Conditions under Different Conservation Practices

Erosion control practices have affected the formation of runoff, and the storage and transfer of soil moisture. In particular, soil moisture condition has tended to dry up and the hydrological environment of soil to deteriorate because of the intensive usage of soil water by forest and grass vegetation.

Soil moisture under the different erosion control practices was monitored for two consecutive years. Soil moisture characteristics in 0 — 1000 cm soil profile (Fig. 4) and soil moisture status under different conservation practices (Table 1) showed that among the conservation practices, soil moisture was the largest in soil-saving dam land, ranging from 6.62% at 1.40m depth to 19.2% at 8.20m depth in soil profile, with an average soil moisture content of 8.98% in 0 — 300 cm soil profile; slope caragana land had the worst soil moisture conditions, ranging from 3.35% at 5.20m depth to 6.71% at 10.20m depth in soil profile, and average soil moisture content was only 4.97% in 0 — 300cm soil profile, lower than the wilting moisture (5.7%). Soil moisture contents under different conservation practices were in order: soil-saving dam land > slope farmland > terraced farmland > terraced orchards > locust land > poplar land > alfalfa land > caragana land.

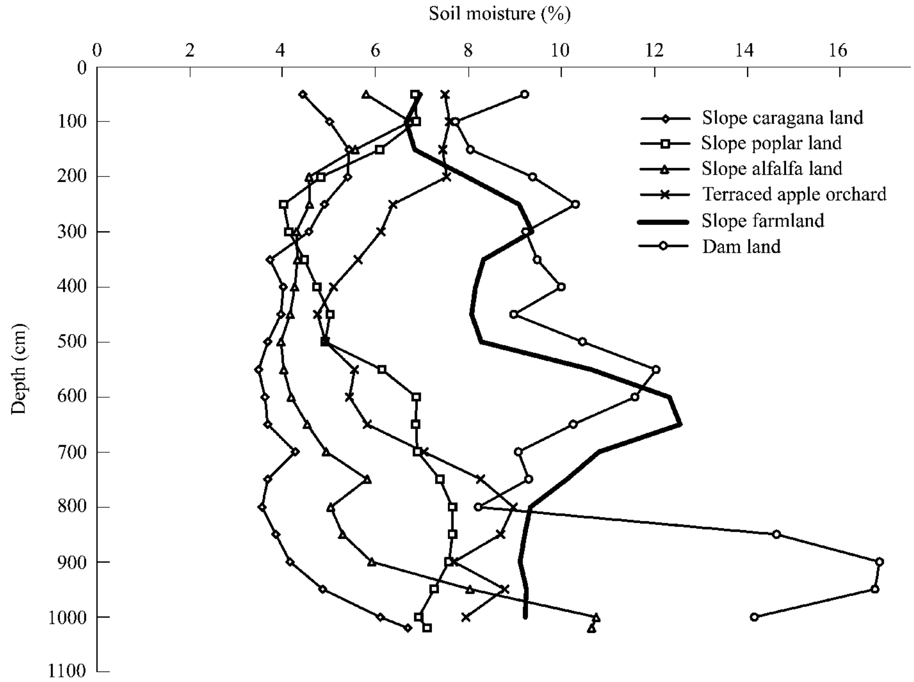

Fig. 4　The soil moisture under various control practices

Rainfall principally influences the soil moisture condition in 0 — 300cm depth[15, 16], and soil moisture is relatively stable below 300 cm. Fig. 4 shows that soil moisture under the conservation practices was lower than that of slope farmland except terraced orchards above 1.75m soil profile and soil-saving dam land, which indicated that the trees and grasses accelerated the depletion of soil water. Compared to the wilting humidity of the corresponding land type there was no "dry soil layer" in slope farmland while "dry soil layer" was in 400 — 460cm depth in apple orchard, with an average soil moisture content of 4.72%; "dry soil layer" was in 280 — 600cm depth in alfalfa land, with an average moisture content of 4.18%; it was in 220 — 350cm depth to locust land and poplar land, with an average moisture content of 4.22% and it was in 0 — 960cm depth in caragana land, with an average moisture content of 4.33%. The reason for the formation of "dry soil layer" was the over-depletion of soil moisture resulting from intensive water absorption by trees and grasses: soil water could not be fully recharged or restored, so that soil was being dried day after day and "dry soil layer" was eventually formed. Due to relatively low water consumption by apple trees and annual crops, soil water could be recharged and restored by rainfall in slope farmland and terraced orchard so that input and output of soil water was basically balanced, and soil water was generally in the status of dynamic equilibrium.

Table 1 Soil moisture regime under different erosion control practices

Depth (cm)	Caragana land (20 a)	Poplar land (23 a)	Alfalfa land (10 a)	Terraced orchard (12 a)	Locust land (26 a)	Terraced farmland	Daml and	Slope farmland
0 ~ 100	4.73	6.88	6.28	7.56	7.93	7.76	8.47	6.83
100 ~ 200	5.29	5.94	5.64	7.53	9.36	7.61	8.38	7.17
200 ~ 300	4.97	4.34	4.49	6.69	4.59	7.36	9.64	8.81
0 ~ 300	4.97	5.48	5.27	7.10	7.06	7.59	8.98	7.82
0 ~ 200	5.08	6.17	5.68	7.53	8.53	7.70	8.59	7.12

Table 2 Soil water storage under different control practices

Measure date	Precipitation (mm)	Soil water storage in 0 ~ 300cm (mm)						
		Slope land	Dam land	Terraced land	Terraced orchard	Timber land	Shrub land	Grass land
2004-04-17 ~ 22	534.0	310.1	384.0	416.1	293.3	257.3	222.6	224.9
2003-04-15 ~ 20		276.6	338.3	339.9	248.1	179.8	179.7	195.5
Water storage change (mm)		500.5	488.3	457.8	488.8	456.5	491.1	504.6

Water storage in soil was the result of dynamic equilibrium of rainfall infiltration and evapotranspiration. Water storage was estimated for 0 — 3 m soil profile under different conservation practices by use of average soil bulk density in 0 — 1 m soil. By analysis of the variability of soil water storage within a full year under the main control practices (Table 2), it was indicated that water depletion was the greatest in artificial grassland, and yearly soil water consumption accounted for 94.5% of the total precipitation. The next was shrub, and water consumption was 92.0% of the annual precipitation. Timber forests used up the least soil water, and water consumption was 85.5% of the annual precipitation. Annual water consumption in terraced land was close to forestland, although the terrace had a high water storage capacity: however lateral evaporation took place on the walls of terraces. The above facts showed that over 85% of the recharged water into soil was evapotranspirated and only less than 15% of annual precipitation was stored in soil even if it was a bumper year of rainfall. If it was a drought year, the increment of soil water would be less or even a negative increment.

The spatial distribution of soil moisture (Table 3) indicated that the north-facing gentle slope land and the terraced land in the gully bottom had the largest soil water storage while orchard and alfalfa land had the lowest. Generally hydrological environment of north-facing slope was better than that of south-facing slope, and gully bottoms were better than hilltops and gentle slopes were superior to steep slopes. The intensive evapotranspiration was the main reason for the difference of soil water storage.

Table 3 Soil moisture condition in different micro-land position in growing season

Position	S-facing slope	N-facing slope	S-facing terrace	N-facing terrace	S-facing steep slope	N-facing steep slope	S-facing gentle slope
Water storage (m^3/hm^2)	960	1200	1035	1155	840	1110	915
Position	N-facing gentle slope	Man-made plat land	Slope alfalfa land	Slope in gully head	Dam land	Plat land in gully	Orchard
Water storage (m^3/hm^2)	1305	1095	780	1005	1155	1065	780

2.4 Comprehensive Erosion Control and Total Evapotranspiration

The conservation practices changed the characters of underlying horizon, and land use pattern change influenced the total evapotranspiration of the watershed. It was difficult to measure evapotranspiration, so the amount of evapotranspiration for the whole watershed was estimated by water balance method in this study. Rainfall infiltration was generally not down beyond the rooted depth (within 3 m depth) in soil profile under the annual precipitation of 400 mm whereas the watershed was covered with thick loess soil, and the deep groundwater was not involved in the soil water cycle. In addition, there was no irrigation implemented. The impact of the yearly change in soil water storage on cumulative evapotranspiration was neglected in this study (partially offset in the cumulative process). Yearly evapotranspiration and cumulative evapotranspiration were calculated with the following equation:

$$E = \sum E_i + \Delta W$$

$$E_i = P - R \tag{2}$$

In the equation, E = cumulative evapotranspiration, E_i = yearly evapotranspiration, P = annual precipitation, R = annual runoff, ΔW = difference of soil water storage before and after erosion control practices were implemented. The average soil water storage before control in the watershed was calculated for the top 3 m soil with the data in table 2 supposing that all land was slope farmland before control. The average soil water storage after control in the watershed was calculated by summing up the product of water storage of each type of land multiplied by its area weight. And ΔW was −12.5mm by calculation based on the data in table 2 and 3. Theoretical evapotranspiration was estimated with formula (2) on the basis of the runoff values calculated with empirical formula (1) under the natural conditions in the watershed. Measured evapotranspiration was calculated with formula (2) based on the runoff data measured at the mouth of the gully. The impact of comprehensive erosion control on hydrological environment of soil was calculated by the difference between the theoretical evapotranspiration and the measured evapotranspiration plus the difference of soil water storage before and after control. Table 4 indicates the cumulative variability of precipitation and evapotranspiration from 1982 to 2000. It indicated that evapotranspiration was closely related to precipitation, accounting for 95.7% — 99.9% of the total rainfall in the watershed. The total evapotranspiration at the early stage of artificial erosion control (1982 — 1985) was close to that under natural control. However the total evapotranspiration was being increased with the advancing of artificial control, and both the area of forestland and grassland and evapotranspiration reached the maximum in 1995 and the total cumulative evapotranspiration increased by 56.3 mm. The emphases of artificial control were shifted to livestock raising for better income during 1995 — 2000, mainly including caged chicken raising and scaled hog raising. Therefore the total area of woodland and grassland was kept stable, and the total evapotranspiration was not increased and its average difference stabilized at about 56 mm, close to the total cumulative evapotranspiration in 2000. It showed that

Table 4　The total evapotranspiration from sixth five-plan to ninth five-plan

Year	6th 5-year plan				7th 5-year plan			
	1982	1983	1985	1987	1988	1989	1990	1991
Precipitation	442	859.5	1389.2	1898.7	2381.1	2723.4	3188.1	3706.9
Measured evapotranspiration	440.6	854.7	1379.3	1867.1	2349.5	2689.5	3153.1	3660.1
Theoretical evapotranspiration	438.2	854	1378.9	1862.2	2336.7	2675.8	3139	3640
Difference	2.4	0.7	0.4	4.9	12.8	13.7	14.1	20.1
Year	8th 5-year plan				9th 5-year plan			
	1993	1994	1995	1996	1997	1998	1999	2000
Precipitation	4096.2	4537.7	4986.3	5378.1	5726.5	6139.7	6408	6789.1
Measured evapotranspiration	4038.9	4474.3	4917.3	5302.8	5649.9	6062.7	6329.4	6710.1
Theoretical evapotranspiration	4021.3	4454.4	4873.5	5259.7	5606.6	6019.7	6285.1	6666.1
Difference	17.6	19.9	43.8	43.1	43.3	43	44.3	44

forest and grass practices played a decisive role in the total cumulative evapotranspiration in the watershed.

3 Conclusion

Erosion control practices and the change of land use pattern in the hilly and gully loess area have had a great impact on the hydrological environment in the watershed through integrated analysis of runoff, soil water storage and evapotranspiration observed for nearly 20 years. Results showed: (1) reduction of surface runoff. Compared to year 1980 — 1985, the runoff out of the watershed decreased by a great margin and runoff coefficient was reduced by 36.1% during 1996 — 2000 with the withdrawal of slope farmland and rapid increase in forest and grass area; (2) soil moisture status varied with different ecological control practices. Soil moisture content of the land with erosion control practices was lower than that of slope farmland apart from terraced orchards and soil-saving dam land. In consideration of wilting moisture of corresponding land types, shrub land, artificial grass land and timber forest land all had "dry soil layer" with different thickness and depth in soil profile, and the thickness was 960 cm, 320 cm and 130 cm respectively; (3) great spatial and temporal variability in soil water storage with different control practices. In the bumper year of precipitation, terraced land and timber forestland had the best soil water storage while artificial grassland had the worst. There was also a significent difference in soil moisture status at different landform positions. Generally the north-facing slopes had better soil hydrological environment than the south-facing slopes, and the gully bottoms were better than the hilltops and the gentle slopes better than the steep slopes; (4) forests and grasses played a decisive role in evapotranspiration. The total evapotranspiration reached its maximum from 1991 to 1995, and the cumulative evapotranspiration increased by 56.3mm, which was inseparable from the increase in forest and grass area.

References:

[1] Yang W Z, Yu C Z. Regional control and evaluation of the Loess Plateau. Beijing: Science Publishing Company, 1992, 190 — 297.

[2] Jiang D S. Soil and water loss of Loess Plateau and control model. Beijing: China Water Conservancy and Hydropower Publishing Company 1997, 106 — 122.

[3] Li Y S. Efects of forest on water circle on the Loess Plateau. Journal of Natural Resources, 2001, 16 (5): 427 — 432.

[4] Li Y S. Loess soil moisture cycle and its impact on land water cycle. Acta Ecologica Sinica, 1983, 3(2): 91 — 101.

[5] Huang M B, Kang S Z, Li Y S. Evolution of moisture environment of small watershed in gully region of Loess Plateau. Chinese Journal of Applied Ecology, 1999, 10 (4): 411 — 414.

[6] Huang M B, Yang X M, Li Y S. Effect of apple base on regional water cycle in Weibei upland of the Loess Plateau. Acta Geographica Sinica, 2001, 56 (1): 7 — 13.

[7] Yang W Z, Shao M A, Peng X D, *et al.* The relationship between water in loess and environment dry of the Loess Plateau. Science in China (series D), 1998. 28 (4): 357 — 365.

[8] Li Y S. Fluctuation of yield 0n high-yield field and disiccation of the soil dryland. Acta Pedologica Sinica, 2001, 38 (3): 353.

[9] Yang W Z. Vegetation building and sustainable development in the Loess Plateau. Beijing: Science Publishing Company, 1998, 42 — 68.

[10] Hou Q C, Han R L, Han S F. Preliminary study on "soil dry layer" problems in artificial grass and forestry land of the Loess Plateau. Soil and Water Conservation of China, 1999, (5): 11 — 14.

[11] Fu B J, Chen L D, Ma K M. The effect of land use change on the regional environment in the Yangjuangou catchment in the Loess Plateau of China. Geographical Journal, 1999, 54 (3): 241 — 246.

[12] He F H, Huang M B, Dang T H. Soil water distribution characteristics in Wangdonggou watershed in gully region of Loess Plateau. Bulletin of Soil and Water Conservation, 2002, 24 (4): 6 — 9.

[13] Huang M B, Zheng S Q, Li Y S. Separation of water reduction benefits by different soil and water conservation measures in watershed scale. Bulletin of Soil and Water Conservation, 2001, 21 (2): 4 — 7.

[14] Shi J H, Xu X L, Yang X Y, *et al*. Study on characteristic of transportation in sendiment of floodwater in the first vice-region of Loes Plateau. Soil and Water Conservation of China, 1991, 10: 18 −19.

[15] Li K Y, Han S F, Cao X F, *et al*. Dynamic of soil water in dryland of northern Shaanxi in Loess Plateau hilly and gully area. Bulletin of Soil and Water Conservation, 1990, 10 (6): 21 −25.

[16] Mu X M, Xu X X, Wang W L, *et al*. Impact of artificial forest on soil moisture of the deep soil layer on Loess Plateau. Acta Pedologica Sinica, 2003, 40 (2): 210 −217.

参考文献:

[1] 杨文治,余存祖. 黄土高原区域治理与评价. 北京:科学出版社,1992. 190 ~297.

[2] 蒋定生. 黄土高原水土流失与治理模式. 北京:中国水利水电出版社,1997. 106 ~122.

[3] 李玉山. 黄土高原森林植被对陆地水循环影响的研究. 自然资源学报,2001,16 (5):427 ~432.

[4] 李玉山. 黄土区土壤水分循环特征及其对陆地水分循环的影响. 生态学报,1983,3 (2):91 ~101.

[5] 黄明斌,康绍忠,李玉山. 黄土高原沟壑区小流域水分环境演变研究. 应用生态学报,1999,10 (4): 411 ~414.

[6] 黄明斌,杨新民,李玉山. 黄土区渭北旱塬苹果基地对区域水循环的影响. 地理学报,2001,56 (1):7 ~13.

[7] 杨文治,邵明安,彭新德,等. 黄土高原环境的旱化与黄土中水分关系. 中国科学((D 辑),1998,28 (4): 357 ~365.

[8] 李玉山. 旱作高产田产量波动性和土壤干燥化. 土壤学报,2001,38 (3): 353 ~356.

[9] 杨文治. 黄土高原植被建设与持续发展. 北京:科学出版社,1998. 42 ~68.

[10] 侯庆春,韩蕊莲,韩仕峰. 黄土高原人工林草地"土壤干层"问题初探. 中国水土保持,1999,(5):11 ~14.

[11] 傅伯杰,陈利顶,马克明. 黄土丘陵区小流域土地利用变化对生态环境的影响. 地理学报,1999,54 (3): 241 ~246.

[12] 何福红,黄明斌,党廷辉. 黄土高原沟壑区小流域土壤水分空间分布特征. 水土保持通报,2002,24 (4): 6 ~9.

[13] 黄明斌,郑世清,李玉山. 流域尺度不同水保措施减水效益分析. 水土保持通报,2001,21(2):4 ~7.

[14] 史景汉,徐雪良,杨秀英,等. 黄丘一副区小流域洪水输沙特性研究. 中国水土保持,1991,7:22 ~25.

[15] 李开元,韩仕峰,曹雄飞,等. 陕北黄土丘陵沟壑区旱地土壤水分动态. 水土保持通报,1990,10(6):21 ~25.

[16] 穆兴民,徐学选,王文龙,等. 黄土高原人工林对区域深层土壤水环境的影响. 土壤学报,2003,40(2):210 ~217.