African Journal of Biotechnology Vol. 8 (19), pp. 4717-4723, 5 October, 2009
Available online at http://www.academicjournals.org/AJB
ISSN 1684–5315 © 2009 Academic Journals

Review

Constructing ecological-protecting barrier: Basic research of rainfall runoff regulation and application in the Loess Plateau of China and its implications for global arid areas

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Accepted 4 September, 2009

Loess Plateau is one of most eco-fragile and poverty-stricken areas in China. Drought and soil erosion are the two major obstacles to restrict economic development here. Rainfall runoff is the leading factor causing soil and water loss in this region. Rainfall runoff regulation and utilization is the inheritance, innovation and development for scientific theories of soil and water conservation in the Loess Plateau, which gives prominence to scientific gathering and detracting of rainfall runoff in terms of space and time and emphasizes on solving the drought and soil erosion by active control means and realizes the unity of regulation, preservation and utilization of rainfall runoff in space and time. The paper analyzed the progress of the applied research of rainfall runoff regulation and utilization from 4 aspects, such as the operational rules of rainfall runoff, the potential of rainfall runoff regulation and utilization, the optimal allocation of rainfall runoff and the environmental effects of rainfall runoff regulation and utilization. It also made the analysis on the current situation of rainfall runoff utilization technology. At last, the paper suggested some cases for rainfall runoff regulation and utilization in the Loess Plateau. Rainfall runoff not only brings about the integration of ecological reconstruction with economic development in the Loess Plateau, but also provides a new approach to the sustainable development as well as removing two of the biggest stumbling blocks, drought and soil erosion, in the Loess Plateau of China, which will provide more information for rainfall runoff utilization in the arid areas of the world.

Key words: Loess Plateau, rainfall runoff, regulation and utilization, basic research, utilization technology, eco-environment.

INTRODUCTION

The Loess Plateau of China covers about 640,000 km2, with 6.67% of the total area of China.Because of bad land use and serious cutting of vegetation, the unique loess structure of point-arris-contacting-frame-multi-core has been destroyed, reducing Loess anti-erosion and causing serious soil and water loss (Zhu, 2006). There are about 454,000 Km^2 of water and soil loss higher than 1×10^3 $t/km^2.a$ in the Loess Plateau, taking about 71% of the total area of Loess Plateau of China, and this region is the most serious area of water and soil loss in the world (Wang et al., 2006). The water resources amount per person in this region is about 541 m^3, and the mean water resources amount per hectare is about 2625 m^3, taking about 22 and 10% of total China, respectively (Tang, 2004; Wu et al., 2005, 2008; Wu and Guo, 2006; Wu, 2007).

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In addition, the above water resources is mainly distributed in rivers, mountains, basin lands and canals with on benefit for extensive slope land in terms of irrigation. Agricultural production in this area mainly depends on the rainfall resources of about 300-500 mm, but this rainfall is concentrated during June to September, taking up 60- 80% of total rainfall, which is not in agreement with the key season for crop water requirement and causes sea- sonable drought for crops (Zhao et al., 1995; Wang and Jiao, 1996; Zhou and Shao, 2008). The Loess Plateau of China has been one of most eco-fragile and poorest regions because of the limitation of soil and water loss and drought. So, solving the above two obstacles is the basis for realizing eco-health and rural economic development in the semiarid and arid area of Loess Plateau of China.

Facing the co-existing problem of soil and water loss and drought in the Loess Plateau of China, how to synchronize the above issues is an important challenge in the field of soil and water conservation. Many researchers studied the cause of soil and water loss through a lot of sited-observation and in/out-room simulation experiments and concluded that rainfall runoff was the main reason to cause soil and water loss in the region with rainfall in storms. If the slope rainfall runoff can be scientifically controlled, deleting the force of soil and water loss and constructing rainfall-runoff regulating and utilizing technology system to make the slope rainfall runoff scientifically gathered and detracted, the dual target of controlling soil and water loss and alleviating drought will be realized (Shan et al., 2002; Wu et al., 2003; Guo and Duan, 2004; Hong et al., 2005; Feng et al., 2007).

Regulating and controlling the rainfall runoff as the measures to reach the above aim has been given more attention. China government has given more priority to rainfall runoff regulation and control such as the State 9th Five Science and Technology Project of Water-saving Agricultural Technology and Demonstration and the State 863 Plan of Modern Water-saving Agricultural Technological System and Novel Products Research and Development, in which there are the above contents and scientific concepts. By the support from these grants, this field has seen its obvious progress and economical, ecological and social effects have been obtained. No doubt, these projects have made the study of slope rainfall runoff technology and utilization advance deeply and extensively.

RAINFALL RUNOFF REGULATION AND UTILIZATION IN LOESS PLATEAU OF CHINA

Since 50's in the 20th century, more efforts have been invested in the comprehensive control and demonstration oriented by soil and water conservation in the Loess Plateau, making some important advances and obtaining better economical, social and ecological effects. But, the general situation of soil and water loss and drought have not been improved in nature, especially in the aspect of soil and water loss in hill-ravine regions, resulting in more loess flowing into the Yellow River. Since the implementtation of stopping-tillage-for-forestry (grass)-engineering, the ecoenvironmental construction has advanced rapidly by planting a large area of trees and grass. But, with time, some issues arise. More planted trees have become dead or small older trees with slow growth for many years. Additionally, a serious soil drying layer appears in the soil surface, accelerating the dearth of vegetation.

In return, the degradation of vegetation and death due to soil water limitation led to difficult recovery of soil water reservoir, causing reduction and instability of grain production in the Loess Plateau of China, in particular during the serious seasonable drought (Wang et al., 2003; Zhao et al., 2004; Zheng, 2006; Zhou and Shao, 2008).

Soil and water loss is a complicated natural phenolmenon, influences by rainfall, landforms, soils, vegetation and so on. Natural factors are the precondition, but artificial factors are the direct cause to accelerate its process. More studies have been reported in terms of the above factors, but more was emphasized on soil actions, especially targeting soil erosion and producing-sand amount. In consequence, little attention was given to the temporal and spatial regulation of rainfall runoff, leading to the study unilateralism of soil and water conservation in the Loess Plateau to some extent. Practically, among the influencing factors, the slope runoff resulted from rainfall is the leading factor to cause soil and water loss and soil is only the target to be eroded. If there is no slope runoff, it is impossible for soil and water loss to occur (Wu and Gao, 2008).

The annual rainfall amount in the Loess Plateau is about 300-500 mm,but the rainfall is concentrated from June to September, producing more runoff and soil sand and resulting in serious soil and water loss, which also leads to the loss of limited water resources available and seasonal drought for crops. The previous studies are lacking of controlling and deleting the force to produce soil and water loss. The famous scientist, Academician Zhu XM proposed that the comprehensive control of Loess Plateau lie in "the realization of reserving all the rainfall and utilizing *in situ*", but less attention is given to its theory and the pathway to be realized, leading to the current passive situation and some issues (Wu, 2007; Zhou and Shao, 2008).

The concept of rainfall runoff regulation and utilization in the Chinese Loess Plateau is to take the slope runoff from rainfall as a major factor by beginning with controlling the slope runoff and scientifically gathering and detracting it to reach the aim of cutting off the slope runoff line and getting rid of soil and water loss, which is an active process of controlling soil and water loss, can realize resource transformation of the limited rainfall runoff by modern agricultural technology and improve drought-caused water deficit condition resulting in high-efficient utilization of soil and water.

The current soil and water conservation measures mainly depends on engineering measures (level terrace, level gouge, district collecting, scale-shaped tunnels and reverse-slope terrace), biological measures (planting trees and grass) and tilling measures to receive natural rainfall as much as possible and make it permeate *in situ*, reaching the aim of reducing soil and water loss. Although the measures is obvious in controlling soil and water loss, its heading off and utilizing for rainfall are transient. The available soil water depends on the rainfall time.

In the Chinese Loess Plateau with concentrated frequency of rainstorms, especially when drought seasons and years occur, the above traditional soil and water conservation measures cannot play efficient roles, which is a common phenomenon annually in the region. The implementation of rainfall runoff regulation and utilization measures not only inherits the advantages of the above traditional ones, but also provides an efficient method to solve drought and water deficit in the region, which is of potential implications for the global arid areas (Stolte et al., 2003; Wu, 2007; Zhou and Shao, 2008; Zhao et al., 2009).

The significance for this method lies in regulating rainfall runoff as a major factor temporally and spatially and reserving the harvested rainfall runoff during rainstorms into storing facilities (vault, pond) for supplemental irrigation at critical stages of crop water requirement (Yang et al., 2005). The method of rainfall runoff regulation and utilization emphasizes the go-aheadism of utilizing rainfall runoff, by which the target can be realized to synchronized solve soil and water loss and drought, realizing the high efficient use of soil and water resources in the Loss Plateau (Wang and Jiao, 2002; Mu and Li, 2004).

The above measures is the new breakthrough for the combination of soil and water conservation theories and practices, which is established from the previous experience and summary and gradually raised to be an optimized-collocation soil and water conservation measures with purpose according to slope rainfall runoff laws. It also emphasizes the unification of regulation, re serve and utilization of rainfall runoff, realizing the double-winning of soil and water conservation and economic effects for farmers, which is the inheritance, innovation and development for soil and water conservation sciences in the Loess Plateau (Wang and Yang, 2005; Wu, 2007).

BASIC STUDIES ON RAINFALL RUNOFF REGULATION AND UTILIZATION

Rainfall runoff laws

Understanding rainfall runoff laws is the precondition and basis for regulating and utilizing rainfall runoff, which has been one of the hot topics in soil and water conservation, water resources and natural geography (Arnold and Fohrer, 2005). Rainfall runoff process is the result of interactions among precipitation and soil surface and other factors, which is a complicated process (Gronsten and Lundekvam, 2006). Previous studies were focused on simulation and natural precipitation data to establish slope rainfall runoff models, seeking critical hydrodynamic conditions of different regulating measures and exploring precipitation runoff laws under different regulating regimes.

At catchments scale, scholars mainly use annual rainfall runoff data to establish empirical statistic models according to the statistic co-relation, which is simple and direct, but discards the spatial variance from soils, vegetation and landforms and others. So, the applicability of models is limited (Zhao et al., 2005, 2007and 2009). With rapid development of 3S, distributing-type water models have been studied extensively and many new models proposed such as SWAT, ANSWERS, HYDROTEL, SLURP, WEEP, SCS and TOPKAPI (Liu et al., 2005; Jia et al., 2005; Zhang et al., 2005).

The above models have played active roles in simulating and predicting precipitation runoff, some of which are also suitable for applying into catchments in the Loess Plateau of China. Liu et al. (2005) applied SCS model to simulate the catchments precipitation runoff process at Wangdonggou, Changwu, Shannxi, China according to landuse, soil types, climate data and others. The simulation result was more consistent with practical observation with 75% simulation precision, but its parameter, CN was obtained by referring to CN-value table and its reasonability is needed for further investigation.

From the viewpoint of water amount balance, some scholars used the distributing-type model concept and GRID data structure of GIS to spatially simulate rainfall and runoff at the catchments of Loess Plateau of China. By comparison with observed data, the simulation result was proved applicable for predicting rainfall runoff, soil erosion and soil water at the catchments of the Chinese Loess Plateau (Zhao et al., 2005).

These models spatially and temporally influence the calculated period of time and units for precipitation runoff in soil erosion and soil water, reflecting the temporal and spatial odds for rainfall runoff and down-surface. Although they have some theoretical basis, they have strict requirement for precipitation and down-surface information and partial parameters are difficult to be determined due to different distracting methods and basic hypotheses. So, these models are difficult to distinguish out roles from different measures, resulting in applied limitation for these models in the Chinese Loess Plateau (Tian et al., 2003). How to apply modern mathematical and physical methods and advanced space analytical means into the description of rainfall runoff conversion and water amount balance at the scale of catchments needs more investigation, which is involved in the temporal-spatial variability from soils, vegetation and landform factors and the applied issues to extend micro-scale models to catchments-scale ones.

The potential to regulate and utilize rainfall runoff

The potential to regulate and utilize rainfall runoff is one of the important basic contents, which also determines the quantity, scale and distribution for the series of measures of soil and water conservation engineering, biology, tillage and chemistry to some extent. Under the context of safe and efficient utilization for precipitation runoff, the study of precipitation runoff amount at different scales by considering its maximum value as the potential is the theoretical basis for efficient use of soil and water resources (Tian et al., 2003; Zhao et al., 2005, 2009; Abdulla et al., 2009; Saleem et al., 2009). This potential is the interacting consequence among precipitation, land forms, soils, vegetation and artificial impacts.

The previous investigation focused on single-factor effect such as precipitation, soils and vegetation and precipitation or soil water content was used simply as the potential, which is lacking in comprehensive assessment. Other methods were mainly concentrated on the construction of empirical statistic models, which are empty of systemic, quantitative, dynamic and comprehensive analysis and deeper understanding for the process and feedback mechanism of the whole system, making the expected effects difficultly perform (Sudheer and Jacobs, 2004).

We analyzed the precipitation resources potential at different scales, studied the relationship between precipitation resources sustainability and sustainable utilization and established different types of recognizing models such as watershed precipitation resources-sustainable type, regulating facility-type water deficit, utilizing pollution-type water deficit and others.

On regional scale, we proposed five evaluation indicators (annual precipitation, controlled degree, vegetation cover, ravine density and soil organic matter) for the precipitation runoff regulation-utilization potential by taking the maximum precipitation runoff amount as the resources value, formed the precipitation runoff-subject mapping with individual indicators by applying GIS-based spatial overlapping, established the quantitative evaluation model for the regional precipitation runoff regulation-utilization potential on the basis of traditional statistic and artificial nerve network methods and protracted the space-distributed digital map of the precipitation runoff regulation-utilization potential in the Loess Plateau, which provides the policy-decision basis for utilizing precipitation runoff resources (Zhao et al., 2007).

Generally, this model still belongs to whole-collecting models with statistic attribute. How to inspect distributed hydrological models and 3S technology to construct the calculation models for precipitation runoff regulation-utilization potential at different scales and how to measure the corresponding parameters *in situ* in field are the important aspects for the basic study of precipitation runoff regulation and utilization in the near future.

The optimum set-up for precipitation runoff

How to coordinate and solve the scientific installing, optimum structure and collocation for different types of soil and water conservation measures is the important issue. Currently, individual measures for soil and water conservation engineering in the Loess Plateau such as engineering, biological and tillage measures are matured, but their scientific collocation has not advanced well, influencing the whole functional performance of these measures. The Soil and Water Conservation Station of Dingxi, Gansu, China conducted a series of studies in relation to this collocation by the guide of ecological location and explored the grand contraposition of regional developing requirement and environmental resources, spatial contraposition of controlling measures and standing-land conditions, technological contraposition of controlling measures and implemented techniques, management contraposition of serving-target requirement and management functions and temporal contraposition of implementing steps and conditions, providing an important practical example for the optimum collocation of precipitation runoff regulation-utilization measures (Hu and Chen, 2006; Zhang et al., 2007).

The contraposition for regulating measures is very complicated. From natural factors, the optimum collocation for precipitation runoff is the important basis of regulating-measures contraposition. The optimum collocation for precipitation runoff is a decision-making problem for a big complex system with multi-targets, including two related aspects of scouring acting force from soil and water loss and partial recovery of drought from precipitation runoff resources utilization.

Recently, optimum models include decomposing-coordination methods and decomposing-collecting methods with multi-methods (Zhang and Xu, 2005; Giesen et al., 2005; Yagmur and Kaydan, 2009). Practi- cally, the optimum collocation for precipitation runoff is more complicated and the restricting factors of resources amount and investment should be considered in terms of grand ecological effects, microcosmic economic effects, interactions of precipitation runoff and soil and water loss and composite-system carrying capability of precipitation runoff and other new contents. So, to establish in-phase optimum-collocation theories, methodology, principles and using patterns for realizing efficient utilization of soil and water resources is the another direction for precipitation runoff regulation and utilization (Arna´ez et al., 2004; Offor et al., 2009).

PRECIPITATION RUNOFF REGULATION-UTILIZATION TECHNOLOGY

The precipitation runoff regulation and utilization is a better way to solve serious soil and water loss and drought in the Loess Plateau, providing more implications for the other similar areas on the globe. Technology for precipitation runoff regulation and utilization is divided into two parts of regulating techniques and utilizing techniques. The concrete measures of regulating techniques are in

Table 1. Jujube benefit comparison of micro-irrigation technology with harvested rainwater in hilly areas.

Irrigation ways/Cultivation ways	Rainfall at reproductive stage (m^3/mu)	Irrigation amount (m^3/mu)	Yield (kg/mu)	WUE (kg/m^3)	Economic effects (RMB yuan/mu)
No-irrigation/traditional cultivation (density<50plantlets/mu)	264.8	0	134	0.51	524
No-irrigation/dwarf and close planting (density:111plantlets/mu)	264.8	0	310	1.17	1240
Tubular irrigation/dwarf and close planting (density:111plantlets/mu)	264.8	169	780	1.79	3015
Drip-irrigation/dwarf and close planting (density:111plantlets/mu)	264.8	50	1145	3.64	4449
Estavel-root-irrigation/dwarf and close planting (density:111plantlets/mu)	264.8	50	1115	3.54	4429
Estavel-root-irrigation+spraying/dwarf and close planting (density:111plantlets/mu)	264.8	53	1320	4.21	5193

Notes: Jujube price is calculated at 4.0 RMB yuans/kg; WUE, water use efficiency.

agreement with previous controlling measures of soil and water conservation in the Loess Plateau. Utilizing techniques are from regulating ones, which are also the inheritance and development and emphasize temporal-spatial collecting of precipitation runoff to realize the optimum resources target for precipitation runoff and possible better effects of soil and water conservation by changing slope inefficient runoff into efficient water resources. Generally, precipitation runoff utilization technology includes harvesting technology, storing technology and irrigation technology.

Selecting rainwater-harvesting materials is the key step in collecting-rainwater engineering sub-system. In the semiarid Loess Plateau of China, the common materials include concretes, plastic films and so on. The main issues of these materials are higher price and cost for use. Recently, soil stabilizer current-collecting material, polymer surface-spraying current-collecting material, and new-type green bio-collecting rainwater material, such as environmental current-collecting material have been applied in treating rainwater current-collecting surface.

The investment for the developed new-type soil stabilizer material (for instance MBER) is reduced by 30-40% compared with traditional concrete material, but its current-collecting efficiency and longevity are the same as concretes. The area cost per unit for the selected surface-spraying organic silicon current-collecting material is only about 0.14-0.42 US dollars/m^2, but the current-collecting efficiency reaches 60%.The selected lichen bio-solidification material can make 0.5 cm of water layer stay for more than 6 h without leakage on its surface (Zhao et al., 2006, 2007; Wu, 2007; Wu and Gao, 2008; Wu et al., 2008; Wang and Gao, 2008). The rainwater-storing facility is an important step for realizing eco-agriculture of rain water harvesting for supplemental irrigation in semiarid Loess Plateau of China. Currently, the common forms include water cellars and water ponds, which are made of clay and concrete for resisting leakage.

Facing the above cellar old technology and single form, our national center has developed a set of part-installing technology for rainwater-storing facility according to different conditions in semiarid Loess Plateau of China, which is made of flexible rubber cellars with better performance and easy to transport and convenient to produce on a large scale. Its cost per unit cubage is reduced by 20% compared with traditional concrete and this new type cellars have been applied demonstrated in semiarid Loess Plateau (Wang and Gao, 2008; Wang et al., 2008).

The pathways of rainwater-harvesting for supplemental irrigation are realized by the following aspects: 1) supplement rainwater at the critical stage of crop water requirement by non-full irrigation principles and methods; 2) apply the partial irrigation method from modern water-saving irrigation technology. The supplemented irrigated water makes the rhizosphere of crop roots humid and crop evaporation decrease the most. This technique makes the irrigated water each time reduce to the lowest, only being equal to 1/5 - 1/10 of the routine irrigation.

Our experiment with 5-year Jujube in Mizhi, Shannxi, China showed that the combination of rainwater-harvesting engineering technology with modern micro-irrigation engineering technology, especially the modern drop-irrigation technology and root-irrigation technology, made Jujube yield go from 310 kg to 1320 kg and water use efficiency from 1.17 kg/m^3 to 4.21 kg/m^3 and economic effect from 1240 RMB yuans to 5193 RMB yuans with 3 times of total irrigation and an irrigation quota of 50 m^3/mu (Table 1)(Wu et al., 2008).

By applying the above combined irrigation technology, we have constructed the biggest national demonstration zone of rainwater-harvesting micro-irrigation engineering technology in hilly areas of Chinese Loess Plateau (Figure 1), forming an important Mengcha Eco-agricultural

Figure 1. Jujube demonstration of micro-irrigation engineering technology with harvested rainwater in the hilly areas.

Developing Model and realizing the organic combination of scientific and technological factors with the transition of land-manufacturing rights and raising the comprehensive effects of hilly lands.

In addition, this rainwater-harvesting micro-irrigation technology has many favorable effects on Jujube quality and such products are also easy to be produced comercially, realizing the dual effects of ecological construction and increased economic input for farmers. 3) Applying traditional easy and simple methods with higher water-saving such as sowing with water, manual spot irrigation, membrane spot irrigation, and water-injection irrigation. By sowing with water and membrane spot irrigation in Zhungeerqi county, Inner Mongolia, China, Li et al. (2007) reported that maize germination percentage reached above 90%, maize yield 8092.33 $kg.hm^{-2}$ and water use efficiency 2.25 kg/m^3 and other irrigation methods only made 65%, 5510.53 $kg.hm^{-2}$ and 1.83 kg/m^3, respectively.

SUMMARY

1) Precipitation runoff regulation and utilization mainly considers temporally and spatially the major factor to cause soil and water loss, precipitation runoff by scientifically collecting and distracting in an actively-regulating manner to solve synchronizedly soil and water loss and drought and realize the unity of regulation, storage and utilization for precipitation runoff, which is the inheritance, innovation and development for soil and water conservation discipline of the Loess Plateau and provides more implications for arid areas in the world.

2) The running law, optimum collocation theories and models, regulating and utilizing potential, resources- environmental effects and comprehensive regulation, and simulation and application for precipitation runoff at different scales in the Loess Plateau are priorities in this field. Green-environmental rain-harvesting materials and new-type storing facility and recharging-materials and technology of soil water reservoir are the developing direction for precipitation runoff utilizing technology.

3) The precipitation runoff regulation-utilization technology is not only a practical one, but also a highly-efficient ecological technique with obvious effect, which is also the important crossing-discipline subject for soil and water conservation. Most of the contents in the current article are the study and practice results from the Loess Plateau of China for many years, which will provide potential reference for the arid and semiarid regions on the globe in terms of regulating and utilizing natural precipitation runoff. Most parts related to regulating and utilizing rainfall runoff need further investigation.

ACKNOWLEDGEMENTS

This work was jointly supported by National Natural Science Foundation of China 40701092), National Science and Technology Supporting Plan (2007BAD88B10), the Key Program of Education Ministry of China (108182), the Supporting Plan of Young Elites of Northwest A&F University, One hundred-Talent Plan of Chinese Academy of Sciences and International Cooperative Partner Plan for the Innovation Team Group of Chinese Academy of Sciences.

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