Estimation of Rainfall Resource Potential and the Utilization System in the Typical Watershed of China Loess Plateau

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Abstract. As the second longest river in China, the Yellow River is noted for its relatively low water discharge as compared with its huge sediment load. The Xiliu Gully and Heilai Gully, two typical watersheds located in the Inner-Mongolia reach of the upper Yellow River and China Loess Plateau area, is a serious soil erosion and water-deficient region, which belongs to the arid and semi-arid inland basin. In the region, water-consumption mainly depends on rainfall, where there contains grassland, cropland and desert and so on. With the development of economy and society of Eerduosi, the problem of water shortage has become a bottle neck of further development. Based on the hydrogeology features in the Loess Plateau Area, the study proposed the concept of rainfall resource potential, which was composed of surface runoff and soil water. A water yield model based on InVEST (the Integrated Valuation of Ecosystem Services and Tradeoffs) was employed to estimate rainfall resource potential of the two typical watersheds. Based on extensive field research and literature analysis, the process of runoff generation, water enriching and transport was concluded. The highly efficient utilization of rainfall resource in different regions was integrated, which were made of silt trap dams, shallow shaft and ponds. The study provided scientific basis for Spatial Distribution of silt trap dams and high efficient utilization mode of rainfall resource resources.

1. Introduction

With the development of economy and society, the problem of water shortage and soil erosion has become a bottle neck of Loess Plateau area further development. Large asymmetrical water resource in area and time was a major factor. China Loess Plateau area belongs to the continental monsoon climate area, where precipitation concentrated in the summer. Due to its unfavorable geographical location, deep buried depth of groundwater and hilly landform, rainfall and runoff was the fundamental form of water supply for the sustainable development of ecology, society and economics on the Loess Plateau. To fight against the even increasing dry area and deteriorating drought situation, it is necessary and urgent to use engineering measures to improve the utilization of rainfall. Moreover, this is the foundation for the sustainable development of dryland farming and rural economy [1-3]. Some theoretical basis and practical experience focusing on surface runoff and soil water was achieved [4-7] A water yield model based on InVEST (the Integrated Valuation of Ecosystem Services and Tradeoffs) was employed to estimate water source Potential capacity of the two typical watersheds. Then rainfall resource potential was calculated. The previous utilization model of the rainwater resources aimed to meet the irrigation,
farmer living water requirement. This study proposed the high efficient utilization of rainfall resource resources that aimed to meet the irrigation, living and production water requirement. It is made of silt trap dams, shallow shaft and ponds. The result of the InVEST model provided scientific basis for Spatial Distribution of silt trap dams and high efficient utilization mode of rainfall resource resources. The study are likely to be useful for guiding the development and use of innovative rainwater technologies, and then help to relieve the problems caused by water shortages on the Loess Plateau while simultaneously eliminate the major cause of soil erosion.

2. Study Area
The Xiliu Gully and Heilai Gully, two typical watersheds, was located in the Inner-Mongolia reach of the upper Yellow River and China Loess Plateau area (Fig. 1). The area of Xiliu Gully and Heilai Gully is 1058 km$^2$, 1356 km$^2$. More than 60% of the area is the hilly and gully region of the Loess Plateau; the altitude is 1003–1568 m. The study area (109° 10′–109° 50′, 39° 45′–40° 30′ N) belongs to a typical arid and semi-arid continental climate; the annual average temperature is 6.6 °C; the annual average precipitation of Xiliu Gully and Heilai Gully is 384.5 mm, 291.3 mm, of which more than 50% is concentrated in June–August, and appeared in the form of heavy storm, the runoff accounts for more than 90% of the whole year. Alluvial soil, and clay soil are the main soil types of the watershed; among them, the alluvial soil is the most widely distributed soil. The soil erosion is very serious due to freely ravins, vast slope area, many rainstorms and human activities [8-9].

Agriculture and animal husbandry were the dominant land-use types in the basin. In addition, grassland and sandy areas account for more than 40% of the entire area. While the unused land and sandy areas decreased. Various government-sponsored soil and water conservation measures implemented in Xiliu Gully began in 1990 with the establishment of farmland, grassland, and forests and the abandonment of all farming activities on slopes above 25 degrees. There were three geomorphic types: a) Hilly and Gully Region, it was located Most of the upper and middle reaches. There was sparse vegetation, serious soil and water loss in the area. b) sandy area, it is a part of the Kubuqi Desert. Fixed and Semi-fixed low dunes was widely distributed. The rate of the water down permeation was high. The runoff formation does not occur in general. c) Alluvial fans, it is located lower reaches. Coming sediment was deposited here. by the end of 2015, the control area of soil erosion had added up to 50592 hm$^2$; The erosion control ratio had been increased to 22.2%. There were 42 key dams, 84 medium and small-scale silt trap dams. The controlling area was up to 311 km$^2$, the silt area was 974 hm$^2$. Aroused by the exchange of water consumption right from agriculture to industry, under the leadership of the local government, 180 silt trap dams will be built in order to retain 3.21 million tons of sediment.

Figure 1. The study area: a the relative geographical location of the watershed and the Yellow River basin; b latitude and longitude coordinates, digital elevation model (DEM) data,
3. Methodology and Materials

3.1. The Concept of Rainfall Resource Potential

When rainfall, surface runoff, groundwater and soil water was used to meet the demands of production, living and eco-environmental construction, they could be called rainfall resource. Because of concentrated rainfall and disaccord processing between rainfall and water demand of crops, there was a big amount of water shortage in the Loess Plateau, rainfall and runoff was main water sources. As lack of surface water resources and deep buried depth of groundwater that cause to difficult to be used. In total, controlling and utilizing effectively the rainfall could increase the capability of soil infiltration, decrease soil loss. Then efficiency of utilization of limited soil and water resources would be greatly improve [10].

Since the available soil moisture was direct water supplier of plants, it is the important component of the water resource. In the study, rainfall resource included surface runoff, available soil water and groundwater. In the aspect of the Loess Plateau, special climate condition and geomorphological types (inhomogeneous spatial and temporal distribution of rainfall, thick soil layer, and runoff yield under excess infiltration, and deep buried depth of groundwater and more than 50 m of unsaturated zone depth) determined that Utilizing rainwater resource recharging groundwater was difficult [11]. Then the dried layer of soil appeared in some regions of the Loess Plateau because of the shortage in recharge of groundwater annually for a long time [12]. Therefore, rainfall resource included surface runoff and available soil water groundwater in the Loess Plateau.

3.2. The InVEST Model

The InVEST model (Integrate Valuation of Ecosystem Services and Tradeoffs) is an ecosystem service appraisal tool developed in 2007 by Stanford University, the World Wide Fund for Nature and The Nature Conservancy. It has been widely used across many regions [13-15]. The water yield module is a large spatial-temporal scale model developed because of water balance principles. Taking advantage of this model, we evaluated water supply services at a regional scale. The aims of this study were defining the spatial distribution of water supply service and the water supply service of -watersheds. The model runs on a gridded map. It estimates the quantity and value of water used for hydropower production from each sub watershed in the area of interest. It has three components, which run sequentially. First, it determines the amount of water running off each pixel as the precipitation less the fraction of the water that undergoes evapotranspiration. The model does not differentiate between surface, subsurface and base flow, but assumes that all water yield from a pixel reaches the point of interest via one of these pathways. This model then sums and averages water yield to the sub watershed level. The pixel-scale calculations allow us to represent the heterogeneity of key driving factors in water yield such as soil type, precipitation, vegetation type, etc. Therefore, the amount of water yield is equal to rainfall resource potential.

The water yield model is based on the Budyko curve and annual precipitation. Annual water yield for each pixel \((Y_x)\) on the landscape (indexed by \(x = 1, 2, \ldots X\)) was defined as follows,

\[
Y_x = \left(1 - \frac{ET_x}{P_x}\right) \times P_x
\]

Where \(ET_x\) is the annual actual evapotranspiration on pixel \(x\) with LULU_x and \(P_x\) is the annual precipitation on pixel \(x\).

The evapotranspiration partition, \(ET_x/P_x\), can be estimated as follows

\[
\frac{ET_x}{P_x} = \frac{1+w_xR_x}{1+w_xR_x + 1/R_x}
\]

Where \(R_x\) is defined as the ration of potential evapotranspiration to precipitation, which is the dimensionless Budyko Dryness index on pixel \(x\) with LULC_x, \(w_x\) is the plant-available water coefficient.
and is a nonphysical parameter to characterize the natural climate-soil properties. $\omega_x$ and $R_{xj}$ can be calculated as follows,

$$w_x = Z \times \frac{AWC_x}{P_x}$$

(3)

$$R_{xj} = \frac{K_{xj} \times ET_{0x}}{P_x}$$

(4)

Where AWC$_x$ is the plant-available water content (in mm) and can be held and released in the soil for use by plants. AWC$_x$ can be estimated as the product of the difference between field capacity and wilting point and the minimum of soil depth and root depth. Z is a seasonality parameter that represents seasonal rainfall distribution and depths. $K_{xj}$ is the plant evapotranspiration coefficient associated with LULC$_j$ on pixel $x$, which is largely determined by $x$'s vegetative characteristic. ET$_{0x}$ is the reference evapotranspiration in pixel $x$, which depends on elevation, latitude, humidity and slope aspect. There are countless methodologies, which range in data requirements and precision. In this study, Pennman-Montieth equation was employed as it generates reference evapotranspiration.

Water yield models require land use and land cover, precipitation, average annual potential evapotranspiration, soil depth, plant available water content, watersheds and sub-watersheds as well as a biophysical table reflecting the attributes of each land use and land cover. (a) Land use and land cover were obtained from the State Key laboratory of Resources and Environmental Information System, Chinese Academy of Sciences, generated, and interpreted based on 1:100 000 Landsat MSS and TM satellite remote sensing (http://www.geodoi.ac.cn/). Land use and cover was divided into seven types: farmland, Forest, Grassland, Waters, Buildup area, desert and others [17]. (b) The model required at least five years of climate data around the year of land use. Annual average precipitation data and temperature and so on from 1981 to 2015 located in the watershed was collected from ‘China Meteorological Forcing Dataset’ [18] (http://westdc.westgis.ac.cn/). (c) A GIS raster dataset with an average soil depth value for each cell was generated based on the The Global Soil Dataset for Earth System Modeling (http://www.geodoi.ac.cn/), including total carbon, total nitrogen, total sulfur, exchangeable potassium and organic carbon and so on [19-20]. (d) Plant available water content (PAWC) is defined as the difference between the fraction of volumetric field capacity and permanent wilting point and is important for crop production; agro-ecological zoning, irrigation planning, and land cover changes. Zhou et al. [21] (2005) estimated PAWC based on physical and chemical properties of soil and its spatial distribution in China. This established the mathematical equation between PAWC and proportion of sand, silt, clay and organic matter in soil. In this study we employ this method to estimate the plant available water content. (e) Based on a digital elevation model (DEM) the watershed and sub-watersheds were generated using Arc SWAT and required shapefile formats. Each and sub-watershed was given only one identification number. (f) In order to run the water yield model a biophysical table is required reflecting the attributes of each land use and land cover type (LULC), containing LULC code, descriptive name of LULC, the maximum root depth for vegetated land use classes in millimeters (non-vegetated LULCs should be given a value of minimal root depth, but a zero value should not be used) and the plant evapotranspiration coefficient for each LULC class. The root depth of main vegetation types was obtained following Chen et al. (2008). We estimated the evapotranspiration coefficient of each LULC type based on Allen et al. (1998) and the InVEST user guide. A Zhang constant should be chosen that characterizes the seasonality of precipitation, with possible values ranging from 1 to 10. In this study, the datasets were acquired from multiple famous research institutions throughout the world, and these datasets have been widely applied in various regional studies.
4. Rainfall Resource Potential

The results of the water yield model are affected by the value of the Zhang constant. Taking into account the subtropical monsoon climate, we tried different Z values from 3 to 10. The model Z parameters were calibrated. We defined the Z value as 6.5. The distribution of estimated actual evapotranspiration per pixel was shown in Fig. 2. The actual evapotranspiration is in range of 133.8-374.8 mm. The average actual evapotranspiration was 306.6 mm. Water Volume of average actual evapotranspiration was $7.40 \times 10^8$ m³. The actual evapotranspiration of sandy area was higher (Fig. 3).

By the analysis of the concept of rainfall resource potential and the InVEST model principle, the amount of water yield is equal to rainfall resource potential. The distribution of estimated water yield per pixel is shown in Fig. 3. The water yield is in range of 0-246.2 mm. The average water yield was 29.2 mm. Water Volume of average water yield was $7.05 \times 10^7$ m³. Fig. 3 showed that the water yield of sandy area and the southern part of basin was higher. Mainstream Area did not produce runoff.

‘fractp’ was estimated actual (evapotranspiration fraction of precipitation per pixel, Actual Evapotranspiration / Precipitation). It is the mean fraction of precipitation that actually evapotranspires at the pixel level. The distribution of estimated fractp per pixel is shown in Fig. 4. fractp is in range of 0.352-1. The average water yield was 0.913. Water yield and fractp were highly correlated. That fractp is equal to 1 means the Area did not produce runoff.

5. The High Efficient Utilization of Rainfall Resource

5.1. The process of runoff generation, water enriching and transport

Based upon the field reconnaissance, the process of runoff generation, water enriching and transport was obtained. It was showed in Fig. 6. Sequence from a to f was sorted from upstream to downstream. There existed different scale silt trap dams. Capacity of Surface Runoff Interception by dams were considerable (Fig. 5(a)). For ensuring the dams safety, a part of water was discharged to downstream. the aim of sediment retention and water conservation can be attained as the result that the moisture content in gully channel soil can be obviously regulated, evaporation of moisture in gully channel soil can be delayed and the capacity of surface water infiltrating into soil is strikingly enhanced by the silt trap dams. Moreover, some of Surface Runoff was intercepted by the reservoir was the big (Fig. 5(b)). There exist exudation of shallow groundwater in the river channel, which did not produce runoff Fig. 5(c). Besides, shallow groundwater or soil water was exudated at bottom of sand dune (Fig. 5(d)). Special attention is given that rainfall infiltrated sand dune, a part of water resources was evaporated, and the other part was stored in Sand Layer. Dry sand bed would reduce soil moisture evaporation. Combined with above result of model results, it could be conclude that the water in the river channel (Fig. 5(e)) of desert came from...
shallow groundwater or soil water. In the downstream, the natural outcrops - spring water appeared (Fig. 5(f)). Then, the Route of runoff generation, water enriching and transport was concluded, which was storing water through silt trap dams/ reservoir→ shallow groundwater/ soil water in the river channel→ shallow groundwater/ soil water in the river channel of the desert→ shallow groundwater/ soil water in the river channel→ the natural outcrops - spring/migration to downstream. To sum up, sand dune or desert was a Warehouse and channel of water, where water loss including evaporation decreased.

Figure 5. The process of runoff generation, water enriching and transport In macroscopic view (a→f: from upstream to downstream)

5.2. The High Efficient Utilization of Rainfall Resource

In general, there were two measures of resourcing of rainfall. a) Resourcing of rain in natural way. It meant that rainfall was stored in soil, then the water was supplied to the growth of plants directly. b) Resourcing of rain in natural way of human intervention. It meant that the water was affected by artificial interference to satisfy the demand for human Production and living, such as soil and water conservation which increased infiltrated water, Rainwater Catchment System. Based upon the field reconnaissance, utilization patterns of water resource included Shallow Well, pond of water storage, flume of water Interception and storage and pond of seepage water for irrigation etc.

Traditional utilization pattern of rainfall resource ignored industrial water consumption. Besides, silt trap dams were not made full use. Combining process of water transport and Models, topography and geomorphology and spatial distribution of rainfall resource potential, the high efficient utilization pattern of rainfall resource in different regions was integrated (Fig. 6). The Source of water was runoff, soil water and shallow groundwater. Engineering measures included silt trap dams system, well and pool. The water resource could be used to satisfy the demand of industry, agriculture and living and so on. Silt trap dams system could make use of runoff and soil water. Well could make use of soil water and shallow groundwater. Pool could make use of shallow groundwater. The water storage of Silt trap dams system could be used to satisfy the demand of industry, agriculture and living and so on. The water storage of Well and pool could be used to satisfy the demand of agriculture and living and so on. Compared with previous studies, Silt trap dams on engineering applications and satisfying the demand of industry on water resource use was added.
6. Conclusion
Rainfall resource included surface runoff and available soil water for the Loess Plateau. The results of the water yield model showed that the water yield is in range of 0-246.2 mm. The average water yield was 29.2mm. Water Volume of average water yield was $7.05 \times 10^7$ m$^3$. water yield of sandy area was higher. Mainstream Area did not produce runoff.

Based upon the field reconnaissance, the process of runoff generation, water enriching and transport was obtained. There existed different scale silt trap dams. Capacity of Surface Runoff Interception by dams were considerable. The Route of runoff generation, water enriching and transport was concluded, which was storing water through silt trap dams/ reservoir→shallow groundwater/ soil water in the river channel→shallow groundwater/ soil water in the river channel of the desert→shallow groundwater/ soil water in the river channel→the natural outcrops - spring/migration to downstream. Sand dune or desert was a Warehouse and channel of water, where water loss including evaporation decreased. Compared with previous studies, Silt trap dams on engineering applications and satisfying the demand of industry on water resource use was added.

When we practice concrete technology measure, we should attach importance to the fundamental improvement of ecology and environment in arid region of Loess Plateau and the collective distribution of agricultural and industrial production for constructing agriculture production configuration of benign material cycle, which includes forest and grass culture, capital construction of farmland, start construction of hydraulic engineering, arranging crops and farming measure rationally, and so on. Integrating operation, we can farthest use natural rainfall to improve rainfall productivity.

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