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Sustainable Development of Arid Rangelands and Managing Rainwater in Gullies, Central Asia

Zheng Li, Wentai Zhang *, Yilahong Aikebaier, Tong Dong, Guoping Huang, Tao Qu and Hexin Zhang

Xinjiang Key Laboratory of Soil and Plant Ecological Processes, College of Grassland and Environmental Sciences, Xinjiang Agricultural University, Urumqi 830052, Xinjiang, China; Liz_94@163.com (Z.L.); akbarilahun@xjau.edu.cn (Y.A.); mr_dongtong@126.com (T.D.); xau_hgp@163.com (G.H.); qtao_xj@163.com (T.Q.); zhx19950826@163.com (H.Z.)

* Correspondence: zwt@xjau.edu.cn; Tel.: +86-0991-8763937

Received: 7 August 2020; Accepted: 9 September 2020; Published: 10 September 2020

Abstract: Along with the global climate change, gully erosion, flood and drought jointly restrict the sustainable development of arid rangeland in Central Asia. Rainwater harvesting (RWH) system in gully is a flexible practice that alleviate complex environmental problems. In the Kulusitai watershed of Xinjiang, China, our study presented a decision-making system using GIS combined with multi-criteria analysis and a field survey to identify suitability of gully for RWH. The results showed that nearly 40% of rangeland belonged to high runoff potential area, and gullies as the runoff collection channel became the potential site of RWH. The selection of RWH systems depended on catchment environment and gully characteristics. Therefore, based on the unique natural conditions of Xinjiang and successful RWH cases in other regions, we discussed some suitable low-cost RWH techniques to restore degraded grassland and promote community development. Our study will provide some suggestions for ecological restoration and pasture management in arid regions of Central Asia.

Keywords: gully erosion; runoff potential; rainwater harvesting; ecological restoration

1. Introduction

Land degradation caused by gully erosion is a long-standing and complex global environmental problem, especially in arid rangelands [1]. Climate change and overgrazing have exacerbated the rangeland water erosion and its consequences in recent years [2,3]. Severe gully erosion causes land fragmentation, destroys grassland resources and reduces livestock carrying capacity of rangeland [4,5]. In addition, gullies tend to enhance drainage and accelerate aridification processes [6]. Under heavy rainfall events, a large amount of surface runoff is rapidly lost through gullies, leading to the increase risk of flooding. Moreover, the waste of water resources will aggravate the drought in these areas. With global warming, extreme rainfall events and drought events occur frequently [7,8], which makes the management of gullies an urgent problem in the development of arid pastoral areas.

Rainwater harvesting (RWH) is defined as "the process of concentrating rainwater over catchments through runoff to be stored and beneficially used" [9]. RWH systems can control erosion and restore degraded land during the green revolution [10]. The gully is a temporary gathering channel of runoff in the process of rainstorm, so gullies are used as potential RWH site in some arid areas. Majalubas (Tanzania) and cisterns (Mediterranean region) collect and store runoff in the gullies for agricultural production, which solves the problem of water shortage in dry season, and then improves water efficiency and productivity in arid areas [11,12]. In addition, people have built dams to retain runoff in the channels, which control the soil erosion of arid rangeland, and maintain the natural function and service of watershed ecosystem. Jessours (Tunisia) and Limans (Israel) create water- and nutrient-enriched patches in gullies, which reduce the risk of flood and effectively improve grassland productivity [13–15]. In 2015, the United Nations mentioned, in "transforming our world: the 2030 agenda for sustainable development", that the implementation of flexible and future agricultural practices would be beneficial for improving land productivity, maintaining ecosystem functions and increasing resilience to climate change, extreme weather and natural disasters [16]. Therefore, gully RWH systems will be effective measure to promote the sustainable development of arid regions.

Previous reports on RWH were mostly concentrated in the Mediterranean, the Middle East, Central Africa and other arid areas. Less attention had been paid to arid rangelands in Central Asia, where research on RWH started late, resulting in few studies related to RWH [2,9,10,17,18]. Central Asia is a typical arid area and an important pasture in the world, so, based on the special natural conditions and the urgent demand for gully RWH technologies, this study evaluates the suitability of a gully for RWH.

Whereas successful RWH systems often depend on suitable sites and technical design, assessing the catchment environment is our priority [17,19]. The formation and development of gullies are closely related to the topography, soil texture and other environmental factors [20]. Environmental factors, such as vegetation and land use/cover also determine the resource potential of runoff [21]. Most scholars used GIS combined with multi-criteria analysis to identify suitable RWH sites [22–25]. This method could judge and weigh the importance of multiple variables and accurately evaluate the runoff potential of the catchment. Gully is an independent system, and each gully has its unique morphological characteristics, due to various environment factors (topography, soil, vegetation) of catchment. The characteristics of channel directly affect the suitability, implementation and cost of RWH systems [22,26]. However, in most scholarly evaluation systems, the characteristics of channels were often ignored. The economic conditions and scientific and technological level of pastoral areas in Central Asia often lag behind other areas, which requires us to consider the catchment environment, but also to integrate channel characteristics into the evaluation system. Only by fully understanding the relationship between the catchment environment and gully characteristics, can the selected RWH technique maximize its potential in the gully. Field surveys are often used to select suitable RWH techniques in smaller areas [17]. This study gathered the parameter information of gully through field survey, and also verified the catchment environment, so as to improve the accuracy of evaluation results.

As such, RWH system in gully is an effective practice to control gully erosion and improve water efficiency in arid rangelands, but how to select a suitable RWH system is the primary problem faced due to various gully characteristics. Our study presents a decision-making system using GIS combined with multi-criteria analysis and a field survey to identify suitability of gully for RWH. This method can help decision-makers to select more flexible RWH systems in gully. The purposes of this paper are: (1) get to know the development characteristics of gully and discuss its relationship with catchment environment in arid rangeland of Central Asia; and (2) to evaluate the suitability of gully for RWH accurately and discuss suitable techniques.

2. Materials and Methods

2.1. Study Area

Our study took place in the hills of Kulusitai watershed, which is located in a region of northwestern China's Yili River Valley, in Xinjiang. The area is a typical arid rangeland with a large number of gullies (Figure 1). Grassland in the study area has been seriously degraded, and the vegetation coverage is 10–50%. The main soil type is Calcisol, which has developed from the parent material of Quaternary loess [27]. The loess parent material contains more sand and silt, and therefore the Calcisols are porous and have a weak bonding strength [28]. During rainfall events, the Calcisols are prone to water erosion.

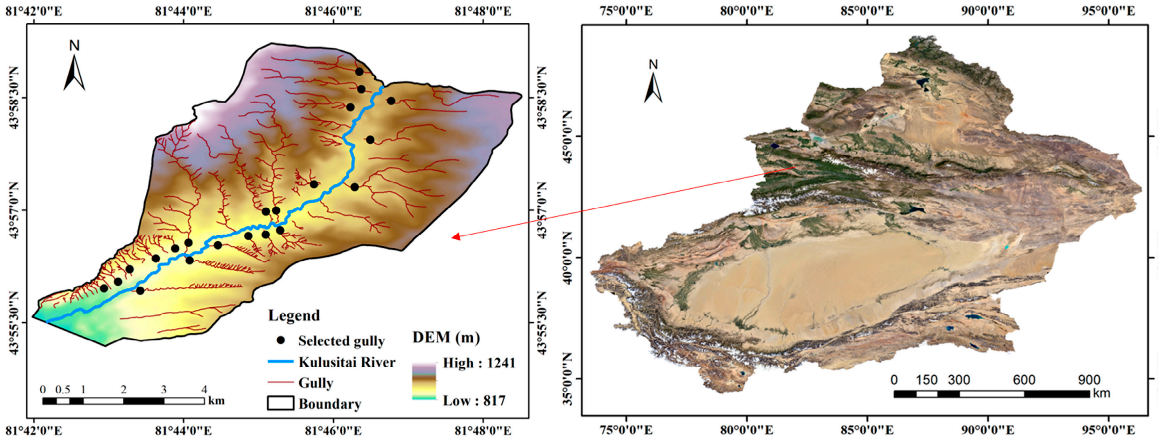

Figure 1. Location of study area and selected gullies.

The climate of study area is temperate continental climate. The rangeland has an average annual temperature of 10 °C and an average annual potential evapotranspiration of 1600 mm. However, the average annual precipitation is about 400 mm, and uneven in seasonal distribution (Figure 2). Precipitation is the only water source in natural grassland, and temperature is main driving factor of grassland water evapotranspiration. There was less evapotranspiration and a higher precipitation supplement from April to May. The evapotranspiration of grassland is so large in the dry season (July and August), but rainfall events are greatly reduced, so grass growth and development are often influenced by drought stress. Therefore, there is obvious seasonal water shortage in this rangeland. When daily precipitation reached 10 mm, we regard the rainfall as a heavy daily rainfall [7]. The contribution of precipitation on the heavy rainfall days to total precipitation is more than 30%, and there is at least one heavy rainfall day every month [29]. During severe rainfall events or high intensity precipitation, rainfall is easily converted into surface runoff, which often lead to floods. RWH techniques transform runoff into available water for grass growth, which are used for ecological restoration of degraded grassland. These special rainfall characteristics have a negative impact on the ecological development of arid rangelands in Xinjiang, but also create opportunities for RWH.

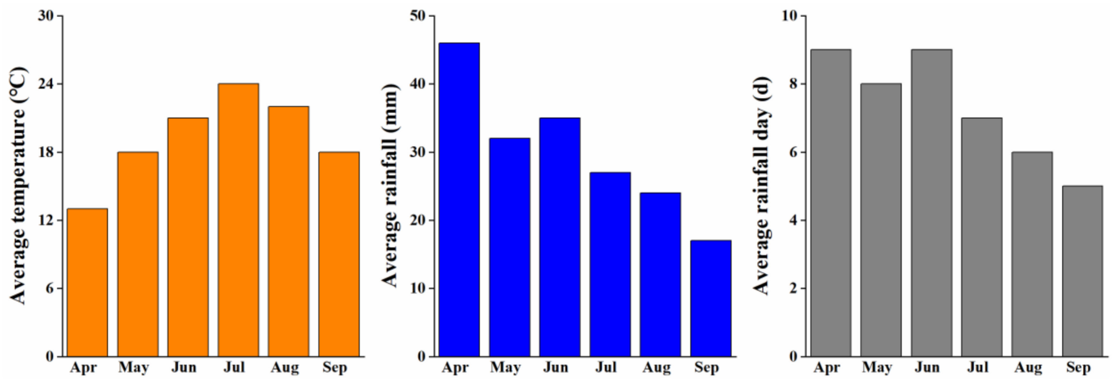

Figure 2. Monthly temperature, precipitation, daily rainfall of Kulusitai watershed.

2.2. Data Source

Digital evaluation models (DEM) with 30 m resolution and remote sensing data (Landsat 8 Operational Land Imager (OLI)) with 30 m resolution were accessible from the Geospatial Data Cloud website (http://www.gscloud.cn/). Land use/cover data was downloaded from the global land cover 10 m resolution map (http://data.ess.tsinghua.edu.cn) [30]. Monthly temperature and rainfall data (from 2010 to 2019) were obtained from the Weather China Website (http://www.weather.com.cn).

2.3. Measurement of Gully Characteristics

We selected 21 gullies in the study area for field survey and analyzed in GIS (Figure 1). The field survey mainly included the measurement of the width and depth of main gully and GPS positioning of some important geographical coordinates, such as gully head (Table 1). After the survey, ArcGIS 10.5 (ESRI, Redlands, CA, USA) was used to calculate the main gully length, area of catchment and other parameters. Principal component analysis (PCA) in SPSS 20.0 (IBM, Amonk, NY, USA) was used to evaluate and classify gullies.

Table 1. Details characteristics of gully and catchment.

Parameter	Measurement and Calculation of Parameters
Main gully length (MGL)	Field survey and calculated in GIS
Total gully length (TGL)	Field survey and calculated in GIS
Main gully width (MGW)	Field survey
Main gully depth (MGD)	Field survey
Circumference of catchment (C)	Field survey and calculated in GIS
Area of catchment (A)	Field survey and calculated in GIS
Relief ratio (Rr)	Rr = H/L, L is maximum catchment length (m); H is height (m) difference between highest point and lowest point in catchment [31].
Drainage density (Dd)	Dd = TGL/A [32]
Slope (S)	Analyzed DEM in GIS
Topographic wetness index (WI)	WI = ln ($Ac/\tan^S$), Ac is the potential contributing area [33]
Normalized difference vegetation index (NDVI)	NDVI = (NIR − R)/(NIR + R), NIR and R are the spectral reflectance in the near infrared band and red band [34]
Land use/cover	Data from Gong's classification system and field survey [30]

2.4. Evaluation of Runoff Potential in Catchment

2.4.1. Criteria Selection

The first step of quantifying runoff potential area was to select appropriate criteria. Based on the guidelines of the Food and Agriculture Organization of the United Nations (FAO) and a literature review, hydrology (rainfall-runoff relationship), topography (slope), land cover/use, agronomy (crop characteristics) and soil (depth and type) were the five important environmental factors. We first selected slope, land use/cover and vegetation characteristics. The accuracy of hydrological model highly depended on the spatial scale of study area and data availability [17]. In Central Asia, there were many pastoral areas similar to the Kulusitai Watershed, which had small spatial scale and little available information. Hydrological models were not applied in our study. We also did not consider soil, because there was only one soil type in our study area. Furthermore, topographic wetness index (WI) was selected to evaluate the runoff potential more accurately.

(1) Topographic wetness index (WI)

WI is a function of slope and catchment area, which accurately reflects the impact of topographic changes on runoff [33]. WI has been applied to predict the spatial distribution of soil water and runoff process widely [35]. The higher WI is, the easier runoff is generated in catchment, indicating the greater potential of runoff utilization.

(2) Slope

Slope is an important index to evaluate runoff potential. Slope affects runoff coefficient and kinetic energy. In the high slope area, the application of RWH system is difficult and requires a stronger structure [19,23].

(3) Land use/cover

Land use can change soil hydraulic characteristics of underlying surface, affect runoff infiltration, and then lead to different runoff coefficients [36,37]. It is generally believed that farmland and bare land have higher runoff coefficient compared with forest and grassland [38].

(4) Normalized difference vegetation index (NDVI)

Good vegetation conditions can enhance infiltration by improving soil structure, and increase surface roughness to delay runoff flow time [39,40]. In arid and semi-arid areas, the increase of vegetation coverage significantly reduces runoff coefficient [38,41].

2.4.2. Data Analysis

We merged 30 m DEM data and Landsat 8 OLI data into a 10 m-resolution spatial data set (WGS-84 geographic coordinate system) using the 'reclassify' tool in ArcGIS 10.5, and then calculated and classified the four criteria (Table 1). As a result of the complex terrain in study area, we divided the WI, and slope into five categories (Figure 3a,b). We used Gong's classification system to classify land use/cover into four categories (Figure 3c). The dominant vegetation type was grassland, and NDVI was divided into three categories (Figure 3d).

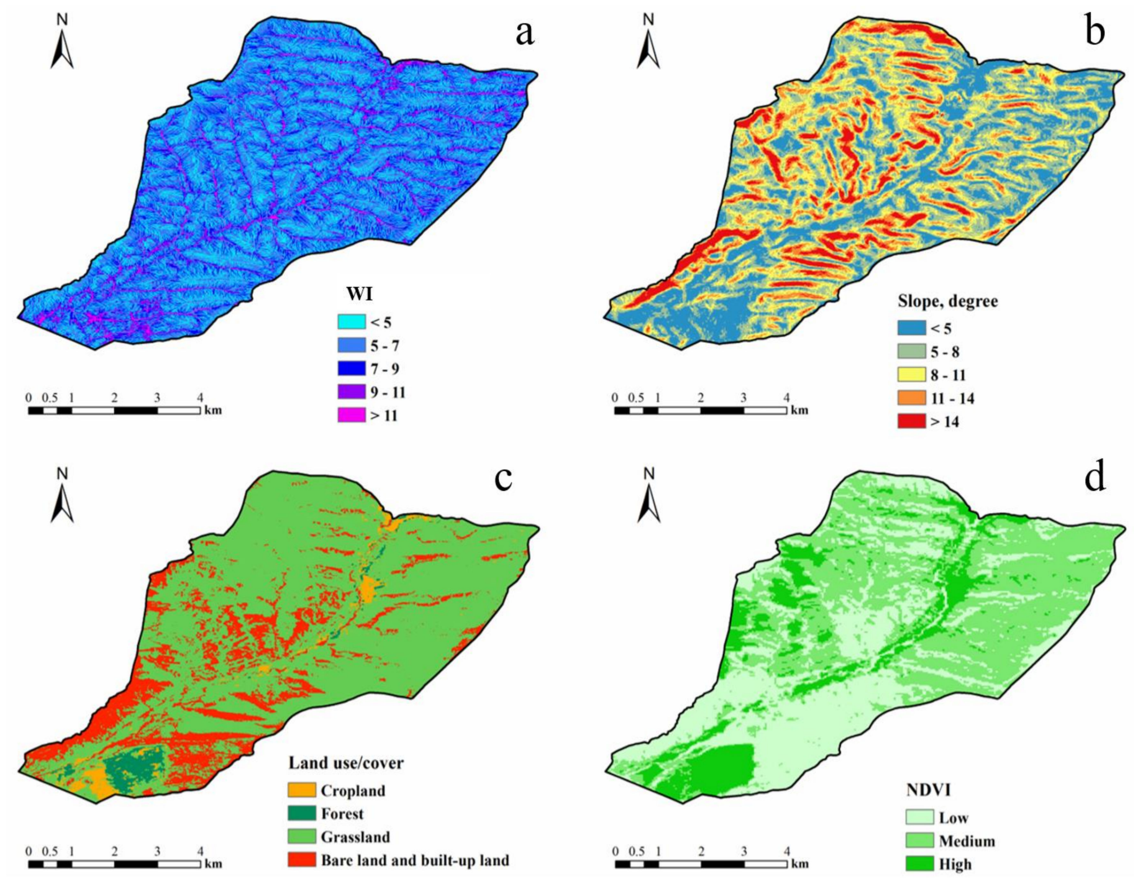

Figure 3. Environmental factors of catchment. (**a**) wetness index (WI); (**b**) slope; (**c**) land use/cover; (**d**) normalized difference vegetation index (NDVI).

The Analytic Hierarchy Process (AHP) is a multi-criteria decision-making method [42]. AHP allows us to understand the contribution of each factor to a given objective and is applied widely to identify runoff potential zones. According to the essential principle of AHP, we made the influence factors of runoff potential organized and hierarchical, and asked experts to score for relative importance of each criteria at each level to form a matrix of pairwise comparisons. We calculated the weight of each layer criteria to upper level criteria by applying a matrix, and then established a multi-level relationship model to quantify runoff potential. The weight of each criteria was calculated by AHP using the yaahp 12.4 software for Windows (Meta Decision Software Technology, Taiyuan, Shanxi, China) (Table 2). In addition, a consistency ratio was used to assess the accuracy of pairwise comparison in AHP [43]. Finally, we generated the runoff potential map by integrating four criteria maps using the 'weighted overlay' tool.

Table 2. Weight of each factor on runoff potential.

Characteristic	Theme Weight	Class	Assigned Class Weight	Consistency Ratio
WI	0.4918	<5	0.0422	0.0370
		5–7	0.0625	
		7–9	0.1367	
		9–11	0.2089	
		>11	0.5498	
Slope (degree)	0.3056	<5	0.0347	0.0523
		5–8	0.0696	
		8–11	0.1411	
		11–14	0.2136	
		>14	0.5437	
Land use/cover	0.1248	Bare land and built-up land	0.6106	0.0523
		Cropland	0.2160	
		Grassland	0.1297	
		Forest	0.0437	
NDVI	0.0778	Low	0.6370	0.370
		Medium	0.2583	
		High	0.1047	

Theme weight' consistency ratio was 0.0181.

3. Results

3.1. *Runoff Potential*

By evaluating the runoff potential, we found that areas with a high density of gullies tended to have high runoff potential (Figure 4a). Especially from the WI map, it could be clearly seen that gullies were the area of runoff collection (Figure 3a). In the southwest of study area, topography fluctuates greatly, and vegetative cover was close to bare land, which made the area become the highest runoff potential area. When heavy rainfall occurred, a large amount of runoff would be generated in catchment and transported to river through channel, and then increased the risk of flood in the lower reaches of watershed. Therefore, it would become a key area for future RWH projects. On the contrary, in the northeast, the terrain was flat, and the vegetative cover had been greatly improved, so runoff potential was far lower than that in the southwest. Nearly 40% of the study area belonged to high runoff potential area (Figure 4b), which meant that there was a large potential for RWH in this rangeland. As a result of different environmental factors, catchments showed different RWH potential, which was of great reference value for understanding the formation and development of gullies and RWH projects in arid rangelands.

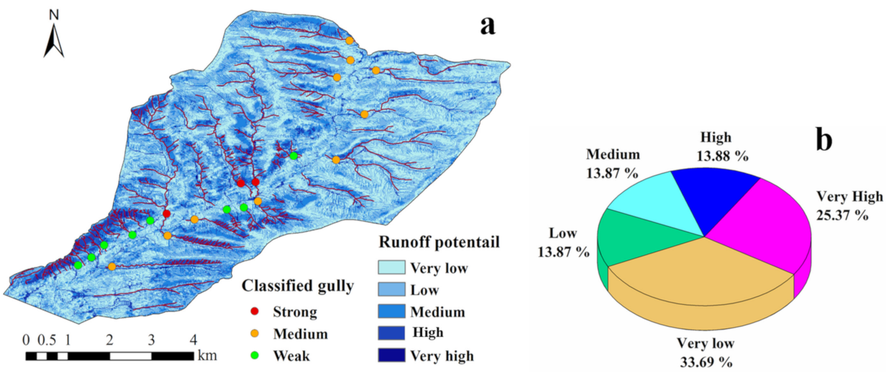

Figure 4. Runoff potential and gullies (strong, medium and weak) location. (**a**) runoff potential map; (**b**) percentage of area covered by different runoff potential.

3.2. Characteristics of Gullies

The results of a field investigation showed that there were severe gully erosion and diversified gullies in arid rangeland. The parameters of 21 gullies were analyzed by PCA (Figure 5). According to the development characteristics, gullies were divided into strong gully, medium gully and weak gully (Table 3). Although catchment of weak gully was small, the higher Dd and Rr enhanced the drainage ability of channels, and runoff was transported out rapidly from catchment. The strong gully had a big catchment, but its Dd was low, and the MGL accounted for a large proportion of the TGL, which led to a large quantity of runoff gathered in the main gully. The wide channel ensured the transport of runoff. The parameters of medium gully were between weak gully and strong gully. The deep main channel was the main feature of medium gully, especially the MGD of three gullies in the south was even more than 5 m.

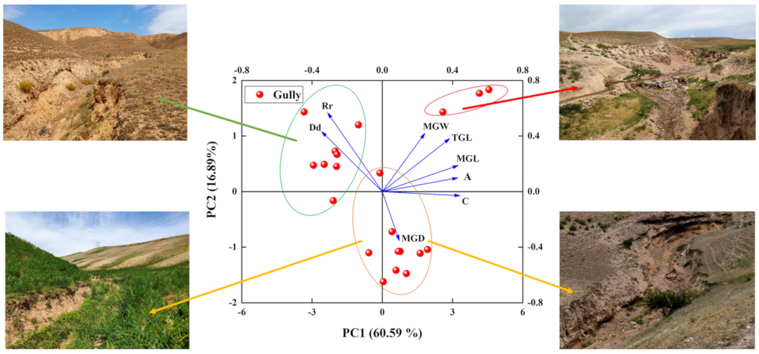

Figure 5. Principal component analysis (PCA) of gully developmental characteristics.

Table 3. Gully developmental characteristics.

Classified Gullies	MGL (km)	TGL (km)	MGW (m)	MGD (m)	C (km)	A (km^2)	Dd (km/km^2)	Rr
Weak gully	0.650c ± 0.05	1.459b ± 0.29	4.62b ± 1.04	1.63b ± 0.12	1.64c ± 0.15	0.13c ± 0.02	12.4a ± 1.75	0.133a ± 0.0049
Medium gully	1.483b ± 0.13	2.293b ± 0.26	5.41b ± 0.84	3.52a ± 0.55	4.60b ± 0.34	0.96b ± 0.14	3.05b ± 0.79	0.067b ± 0.0064
Strong gully	3.300a ± 0.27	6.366a ± 1.13	9.97a ± 0.70	1.71b ± 0.22	7.96a ± 0.71	2.43a ± 0.31	2.57b ± 0.17	0.091b ± 0.0045

Lowercase letters indicated a significant difference at the 0.05 level.

4. Discussion

4.1. Relationship between Gully Characteristics and Catchment

Weak gully catchment had the highest runoff potential. The steep slope provided high kinetic energy for runoff. The critical vegetative coverage for soil and water loss control was 40% in our study area [44]. The vegetative coverage in weak gully catchment was far less than the critical value, and the sparse vegetation would further enhance the sensitivity of gully erosion [18,45,46]. Therefore, gullies were very easy to form in high runoff potential areas, which was the reason why the Dd of weak gully was much higher than that of strong gully and medium gully. Moreover, due to small catchment, the runoff transported from the catchment to the channel was less. The erosion intensity of runoff on the main gully was weakened [47], and the width and depth of weak gully were smaller.

The catchment of strong gully was large, and elevation drop was even more than 300 m. Compared with weak gully catchment, the vegetation and terrain conditions in strong gully catchment were improved, and runoff potential was reduced. Therefore, large scale catchment would not necessarily result in higher Dd, and the same result also appeared in Northeast China [45]. Previous studies had demonstrated that channel width was strongly related to runoff flow [48]. Under heavy rainfall events, major runoff concentrated in gullies, which intensified the erosion of main gully, and then widened the main gully width.

The runoff potential of medium gully catchment was the lowest, but area of catchment was still much larger than that of weak gully. The huge volume of runoff would also be generated in catchment, which increased the erosion of main gully. However, different from strong gully, the main gully erosion of medium gully was mainly reflected in MGD. Headcut retreat, widening and deepening were the typical erosion processes for gullies, but the contribution of these processes might be different due to various catchment environment [6,49]. The depth of channel was closely related to soil erodibility and shear stress of runoff. The soil erodibility K of grassland in this area was about 0.08 $t \cdot hm^2 \cdot h/hm^2 \cdot MJ \cdot mm$, indicating that the soil was prone to water erosion [28]. During the field survey, we found that gully banks of medium gully formed steep steps. The initial step height significantly increased the shear stress of runoff. The overland concentrated flows with potential energy would cause severe plunge pool erosion, and then acted on the channel bed [50]. With the continuous erosion of runoff, headcut would gradually retreat and channel would deepen.

4.2. Selection of Suitable RWH Techniques in Gully

In the case of heavy rainfall, runoff was easily generated in weak gully catchment, and the volume of flow collected in channel was small. At the same time, runoff would be rapidly lost from the catchment due to strong drainage capacity of gullies. The earth check dam with biological control measures (similar to Jessour, Figure 6a) was a suitable RWH system for weak gully. These dams allowed on-site retaining of runoff in channel and plant roots increased runoff infiltration [13,51]. Runoff decreased in volume and speed gradually as it passed through each earth check dam. In addition, dams maintained high available water content in the gully soil, improved soil fertility and vegetation conditions, which was conducive to restoration of pastureland [14,15,52]. The width and depth of weak gully were small, so the construction cost of earth check dam was low and could be used widely in arid rangelands' gullies.

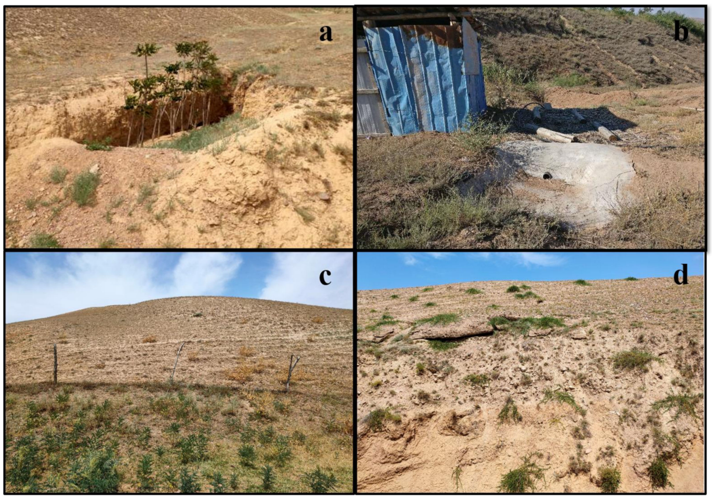

Figure 6. Suitable rainwater harvesting (RWH) techniques in arid rangeland. (**a**) earth check dam; (**b**) water cellar; (**c**) fence; (**d**) vines on the gully wall.

Strong gully had a large catchment with high runoff potential, which was easy to cause flood in the process of heavy rainfall. Although floods were destructive, appropriate RWH systems transformed floods into green water resources in arid rangeland. There were two problems in the construction of dams: one was technical difficulty; the other was high cost. We could build flood diversion channels and reservoirs to collect and store huge amounts of runoff. The flood diversion channel greatly reduced runoff volume in main channel and dispersed impact force of flood. The diverted flood was used to supply irrigation [53]. Storing runoff effectively solved the local seasonal water shortage problem. For example, storing runoff in a simple reservoir saved the runoff that was lost in three days for 40 days in Ethiopia [54]. The stored runoff would also be used for crop irrigation and vegetation restoration (Figure 6b) [10,55], and in desert areas of China, farmers even used the flood to develop aquaculture [56]. Water storage systems, such as water cellar and reservoir, transformed runoff into available resources and helped the green development of arid pastoral areas.

The runoff potential was low in medium gully catchment in the north, but grass was abundant in the lower part of the slope (Figure 5). In view of this special vegetation distribution pattern, we could refer to Tunisia's tabias. We regarded the entire slope as runoff area and developed artificial grassland in the gully and its adjacent areas. Artificial grassland collected runoff from runoff area and stored it in the soil [57]. Some herdsmen had fenced the grassland (Figure 6c). Moreover, we also needed to use simple RWH techniques to further improve grassland productivity. Loose rock dams and branch bundles, made of local materials, might be effective for lessening gully erosion and restoring degraded rangeland [58,59]. In the south, the medium gully had steep gully walls, which was the best place to build dams. Compared with weak gully, the dams retained more runoff because of deeper channels, and steep walls reduced water evaporation in the channels effectively. [23,60]. However, the dykes had to be more robust to resist runoff's forces. In addition, the erosion of gully wall could be controlled by planting lianas (Figure 6d). Some plants with medicinal value would also bring additional economic income to local herdsmen and farmers.

5. Conclusions

About 40% of the low mountain rangeland in Kulusitai watershed belonged to high runoff potential area, which was also the area of gullies. As the runoff gathering place, gullies became suitable sites to carry out RWH projects in arid pasture.

The environmental factors in catchment led to different runoff potential and diversification of gully morphology. According to the development characteristics, gullies were divided into strong gully, medium gully and weak gully. The runoff potential of weak gully catchment was the highest, which also led to the highest drainage density. The deep main channel was the main feature of medium gully, but runoff potential of catchment area was the lowest. Strong gully had a large catchment with high runoff potential, main gully length and width were much larger than those of the weak gully and medium gully.

Our study presents an approach combined runoff potential of catchment with gullies characteristics to further evaluate suitability of different gullies for RWH, and discusses some low-cost RWH techniques suitable for local area. Herdsmen can select flexible RWH techniques to restore degraded grassland and develop farming and aquaculture. The RWH systems in gullies will produce huge ecological benefits (improve ecosystem service value) and social benefits (increase herdsmen's economic income) in future, which has significance for the sustainable development of arid rangelands in Central Asia.

Author Contributions: Conceptualization, Z.L., W.Z. and Y.A.; field survey, Z.L., W.Z., G.H., T.Q. and H.Z., methodology and software, Z.L. and T.D.; formal analysis, Z.L. and Y.A.; writing—original draft preparation, Z.L.; writing—review and editing, W.Z., Y.A. All authors have read and agreed to the published version of the manuscript.

Funding: The research was supported by the National Natural Science Foundation of China (Grant No. 41761059) and the Joint Project of Nanjing Agricultural University and Xinjiang Agricultural University (Grant No. KYYJ201903).

Acknowledgments: The authors thank the editor and anonymous reviewers for their insightful and constructive comments.

Conflicts of Interest: The authors declare no conflict of interest.

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