A GIS approach to determine locations for rainwater harvesting in Haiyuan, Ningxia, China

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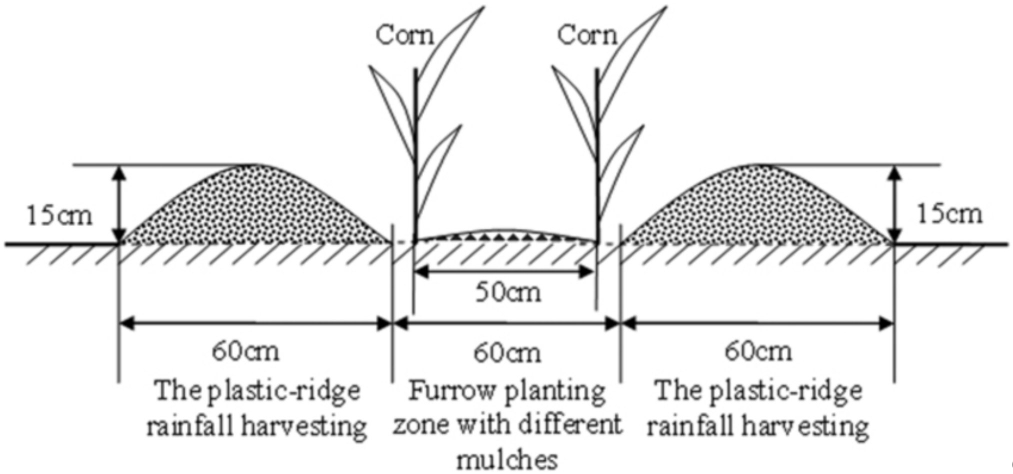
Rainwater harvesting–A solution

As water scarcity continues to be a critical issue in less developed countries, rainwater harvesting offers a promising solution to augment water resources sustainably. The ridge and furrow method is a highly suitable rainwater harvesting technique for China due to its compatibility with the country's topography, climate, and agricultural practices. By integrating geospatial data on rainfall, land cover, slope, soil types and drainage network, a GIS suitability model was developed to assess the suitability of different locations for rainwater harvesting systems. Generally, the study area is ideal for ridge and furrow method, with 64% of the area showing high suitability value (>= 7). This study provides valuable insights for policymakers and urban planners in identifying optimal sites for rainwater harvesting infrastructure, thus supporting water resource management efforts and promoting sustainable water practices in China.

INTRODUCTION

Due to population growth, increasing food demand and ecological service demands, water scarcity has become a global challenge, especially for some less developed countries like China and India (Mekonnen and Hoekstra, 2016). Water scarcity is caused mainly by natural climatic deficient water quantity, and pollution of usable water sources (Jiang, 2009). Regarding this, rainwater harvesting has been suggested as a highly available source to mitigate the problem. Rainwater harvesting (RWH) refers to technology to collect and store rainwater. As an example, RWH, rainwater has been widely used for domestic and agriculture applications. In South Africa, people collect and use rainwater as a supplement irrigation source to help develop agriculture in arid and semi-arid areas (Jensen et al, 2003). Ridge and furrow is an in situ rainwater harvesting method that collects the rainwater on the site. It uses slope to collect the rainwater, and store it at the furrows. It's commonly combined with plastic flims (mulching) to improve the efficiency. Different from other in situ rainwater harvesting methods, ridge and furrow is featured by easy construction, combined closely with the cropland and relatively lower cost (Liu et al, 2022). This method is widely applied in Africa (Jensen, 2003), and tested in Ningxia, China, which shows the ability to significantly improve utilization efficiency and yield (Zhang et al, 2022). Considering the actual situation of China where food security is a top priority, ridge and furrow, as an effective and affordable agricultural rainwater harvesting method, can be more feasible than other methods. With GIS and remote sensing (RS) data, sites suitable for certain RWH methods that are most promising in China can be presented on maps (Ammar, 2016).

This research has selected Haiyuan county, Ningxia, which is an important food production province in northern China, as the study area, and aims to (1) identify the RWH methods that are most applicable and consistency with the economy and society in China and (2) Conduct a GIS analysis to determine areas that meet the requirements of the water harvesting.



(Ren et al, 2016)

METHODOLOGY

Study area

Ningxia is a province that settles in the middle of the continent, in northwest China, with a typical temperate continental climate and Annual precipitation between 150 and 600 mm (Li et al., 2021). Water supplements is the biggest problem that lies in front of the development. The province can be divided into three parts: The northern plain, the middle arid area and the southern mountainous area. The Yellow River flows through the northern plain of the province, which contributes as the main water source for irrigation. The middle arid part and southern mountainous parts far away from the Yellow River are facing serious desertification problems (Yang, 2003).

The study area, Haiyuan county, settled in the middle and southern part, was evaluated as one of the most inhospitable areas in the world by the United Nations World Food Programme. To mitigate water scarcity, in 2003, Ningxia built RWH facilities along the streets to collect rainwater for domestic use (Jiang, 2013). For agriculture use, ridge and furrow along with mulching techniques are the most widely tested RWH methods in China (Jiang, 2013), and researchers found it can also be applied in Ningxia (Zhang, 2022).

Research data

This research uses five criteria to describe the RWH process, the rainfall, land use type, soil type, slope and drainage network, which reflect five aspects: climate, hydrology, slope, agronomy and soil conditions.

The data used in the study were:

- The 30 m pixel size ASTER DEM obtained from the USGS Earth Explorer website.
- The meteorological data collected from Historical Dataset of Ground Meteorological Observations in China (Annual Values), National Meteorological Science Data Center
- The soil data from the FAO soil map of the world.
- Land use/land cover data derived from Landsat satellite images (Landsat 8, 30 m resolution) from the USGS website.

Conditions and weight distribution

The model built by the ArcGIS program was developed to find a suitable map for rainwater harvesting. This model generates suitability maps for rainwater harvesting by integrating different criteria maps using weights. For this study, pairwise comparison was used to carry on Analytic Hierarchy Process (AHP) in order to get the weights for each criterion. Developed by Saaty, this method distributes the weights and importance according to the importance of one component against the other (Saaty, 1977). All criteria are combined by applying a weight to each followed by a summation of the results to yield a suitability map.

The results of relative weights of each criterion are illustrated in table 1 ($cr<0.1$)

The suitability modeller transforms all the maps into suitability maps. For example, the rainfall map in the suitability modeller is presented by the suitability of the rainfall of each point. If the rainfall is lower than the minimum rainfall for the rainwater harvesting method, the value on the map will be low and unqualified, and all the other layers. The eventual suitability map is the result calculated by all the layers input with weights, that each point on the map has an evaluation for suitability.

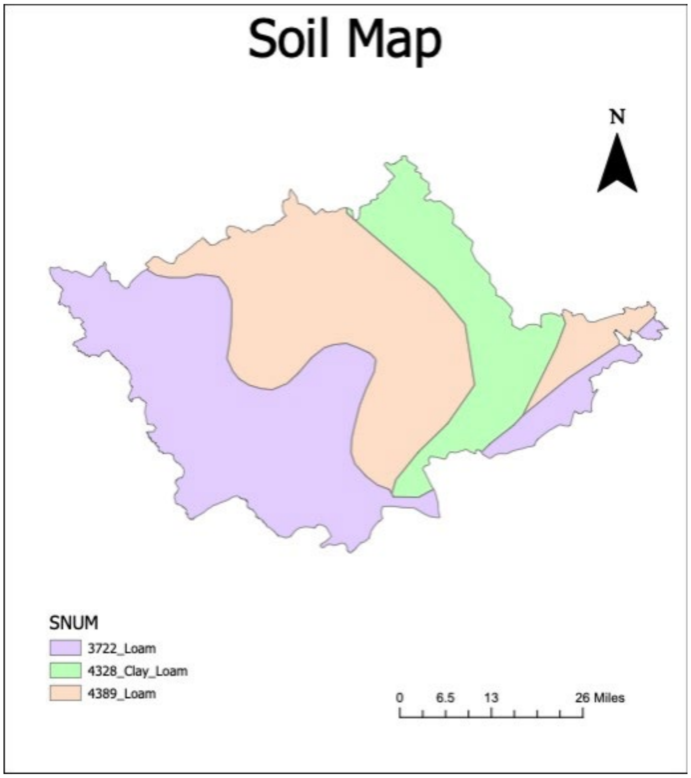
This research gives the highest weight to rainfall from the climate data. It is the foundation of the research. Hydrology and slope are also important. In former research, people used drainage networks and slopes together with the climate data to represent the real hydraulic pattern as they also affect the runoff and residence time for rainwater (Ammar, 2016). The quality of data, also, has an influence on the weight distribution. Land cover and soil data have a coarse resolution. To minimize the influence of error, this research distributes less weight for both land cover and soil types.

Table 1. Weight distribution

Category	Priority [%]	Rank
Rainfall	35.4	1
Drainage network	17.0	3
Slope	24.0	2
Land cover	15.3	4
Soil type	8.3	5

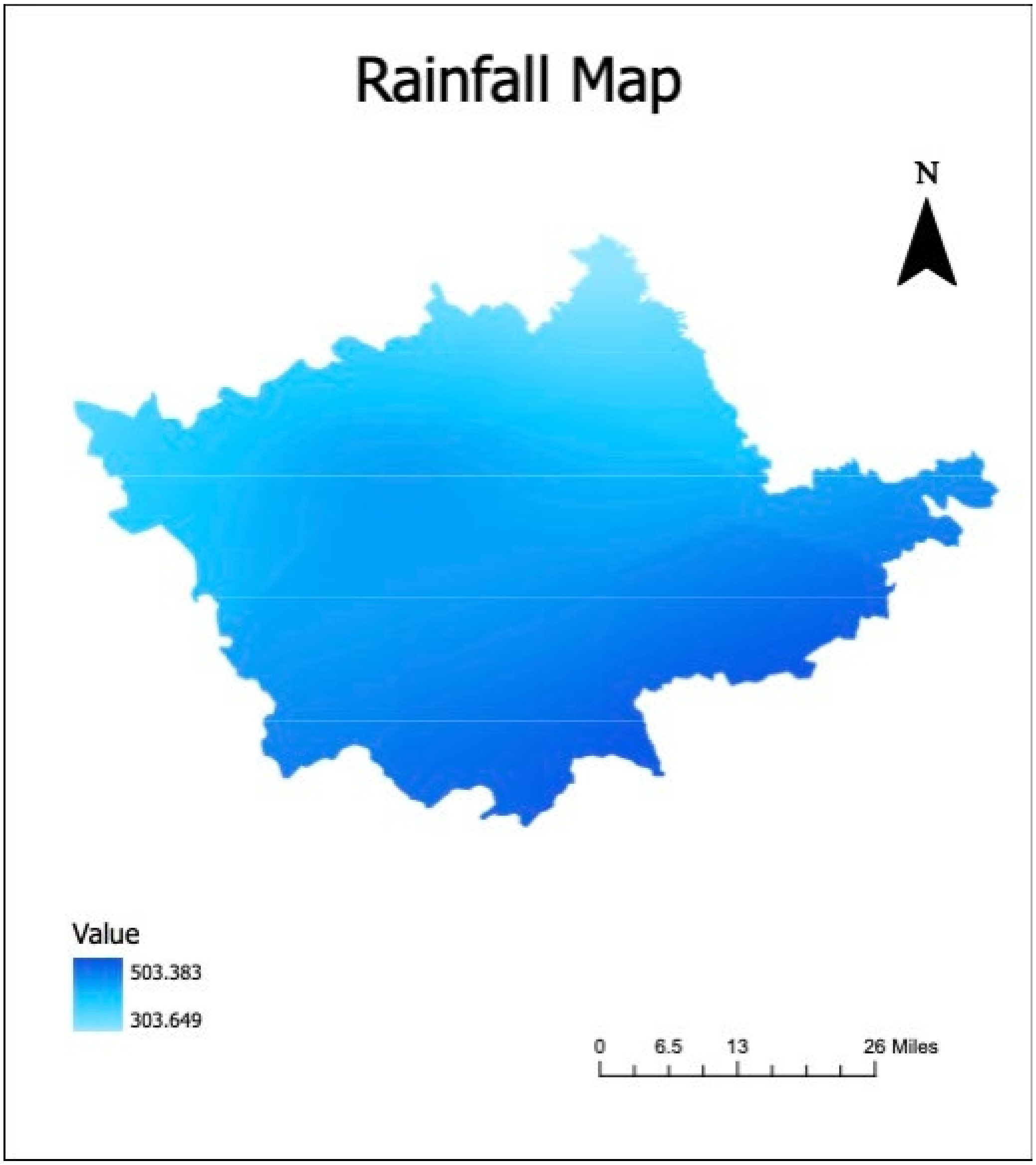
RESULTS

Soil map



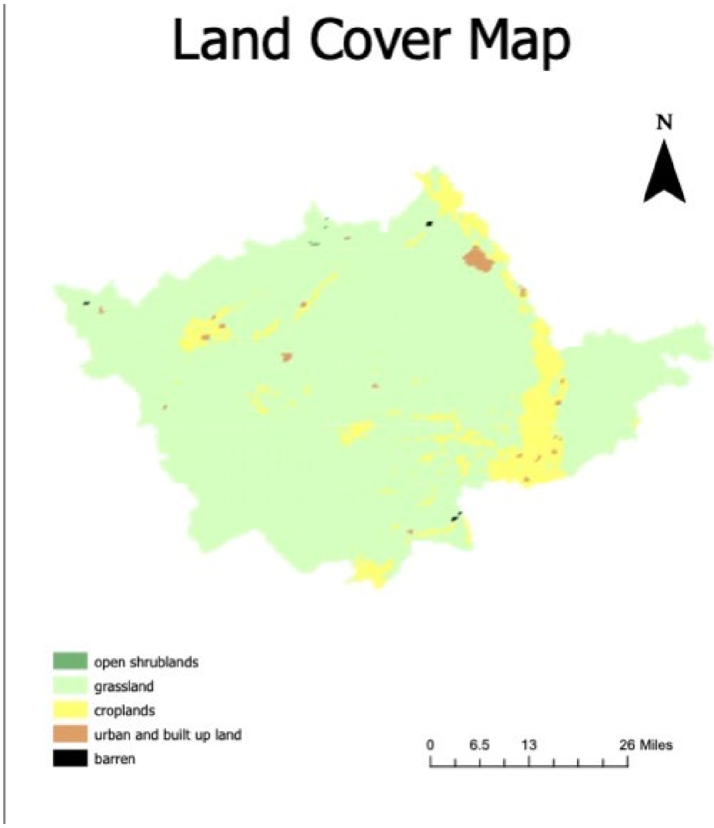
The located soil map is created based on the FAO digital soil map of the world. Three different types of soil are in the study area according to their code (3722-loam, 4328-clay loam, 4389-loam), but 2 of them are the loam(3722-loam, 4389_loam) with differences in the components. According to a former study, the ridge and furrow method as an in situ rainwater harvesting method, can be applied on loam, clay, sandy clay and sandy loam (Adham, 2018). The difference in soil texture influences the infiltration rate, and thus determines the amount of water the soil profile can store and consequently the rooting depth. High water holding capacity is needed for survival of crops because rainfall is sporadic. In this case, clay loam would have a lower infiltration rate that makes it more suitable for rainwater harvesting. According to the description given by FAO about 3722-loam and 4389-loam, 3722 has slightly higher proportion of the coarse particles. As a result, for further analysis, higher suitability will be given to the areas with 4328-clay loam, followed by 4389-loam soil and 3722-loam soil.

Rainfall map



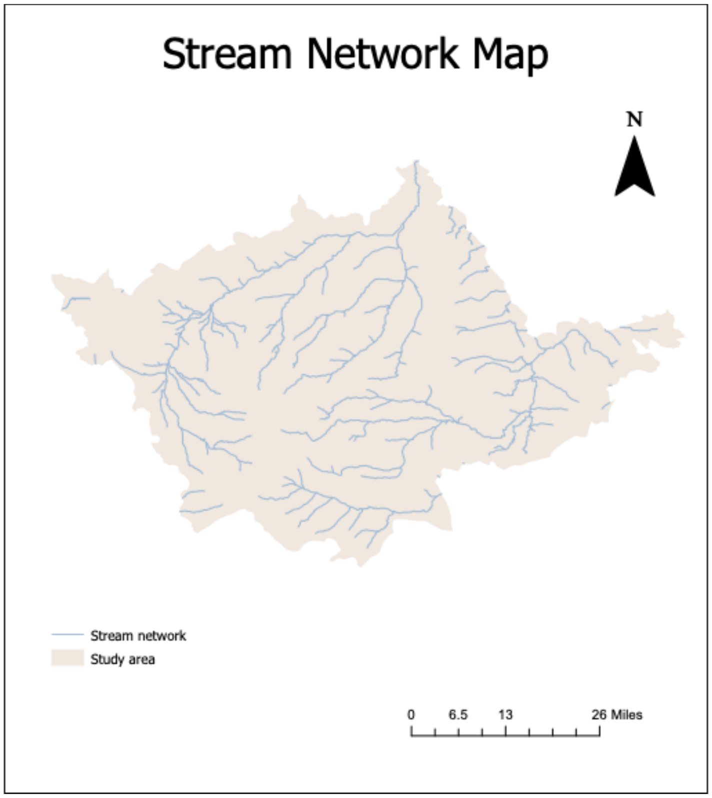
The rainfall map was created by interpolation tools using Historical Dataset of Ground Meteorological Observations in China (Annual Values), which is derived from the National Meteorological Science Data Center. Using the inverse distance weighted (IDW) interpolation tool to interpolate, a map with the data was derived. The results show that, in 2022, the lowest rainfall in the study area was 303 ml at the north-east corner and the highest rainfall was 504 ml at the southern mountainous part. Through literature review, the rainfall information of areas suitable for ridge and furrow method is not specified. To define the lowest edge for precipitation, the research refers to similar in situ RWH methods such as terracing and ponds (Ziadat, 2012), together with a former research testing the ridge and furrow method carried out in Ningxia (Zhang, 2022). The whole area was given a high suitability in terms of the precipitation.

Land cover map



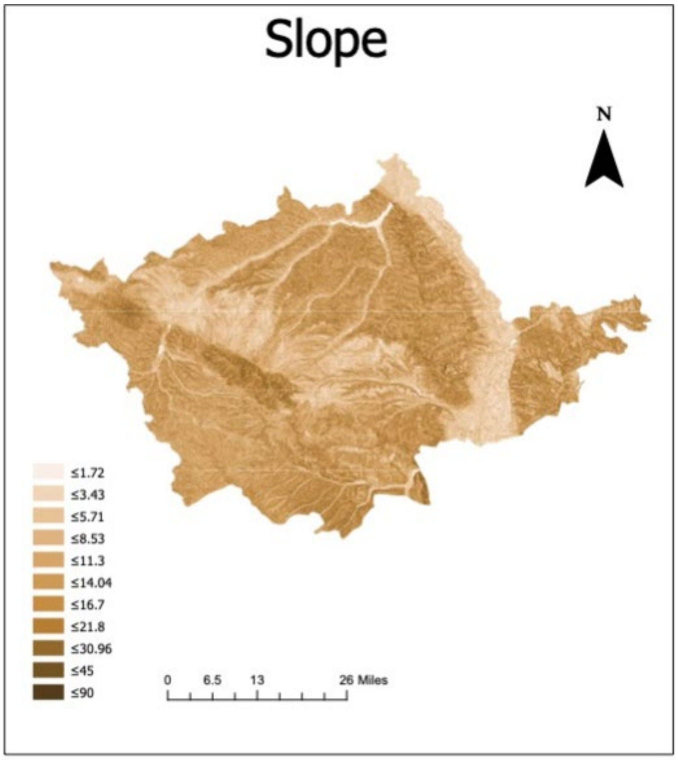
Land cover map uses the FAO land cover map of world MODIS MCD12Q1 V6 data set derived from the USGS website. The study area is mainly made up of shrubland, grassland, cropland, urban, built up land and barren area. This research gives highest suitability to the cropland for they are the ideal sites for in situ rainwater harvesting, including ridge and furrows. At the same time, the study area is a very important crop production base in northern China, choosing to equip the in situ rainwater harvesting in existing cropland brings significance for water source distribution and the future production pattern. Open shrubland, as referred to in the former in situ rainwater harvesting application research, is also suitable for ridge and furrow methods (Mati, 2006. Ziadat, 2012. Ammar, 2016). However, urban areas and barren land are considered as not suitable for rainwater harvesting for the RWH in urban area are mostly for domestic use and have different criteria.

Drainage network map



Drainage network of the study area is extracted using the hydraulic toolkits from the DEM (Ziadat, 2012). To get a more specific suitability map, the researcher uses the spatial analysis tool to calculate the distance from the river. And then generate a transformed suitability map for analysis, so that within the fixed distance, the sites closer to the drainage network will have a higher suitability.

Slope map



The slope is derived from DEM. Through literature review, the suitable slope for in situ rainwater harvesting is different from method to method, where terracing can be applied with the highest slope, 30 degrees. Ponds and pans need to be the lowest point of the area so that water can be naturally collected, so it needs a slope less than 5 degrees. Most in situ rainwater harvesting methods need slope less than 10 -15 degrees (Mati, 2006. Ziadat, 2012. Ammar, 2016). For ridge and furrow method is usually applied in the croplands, this research set the ideal slope to be less than 10 degrees, while a more even morphology can be better for construction, and also for prolonging the retention time for the rainwater. The research uses functions to describe the suitability, the higher threshold is set as 10 degrees, above this point the suitability for slope is going to drop.

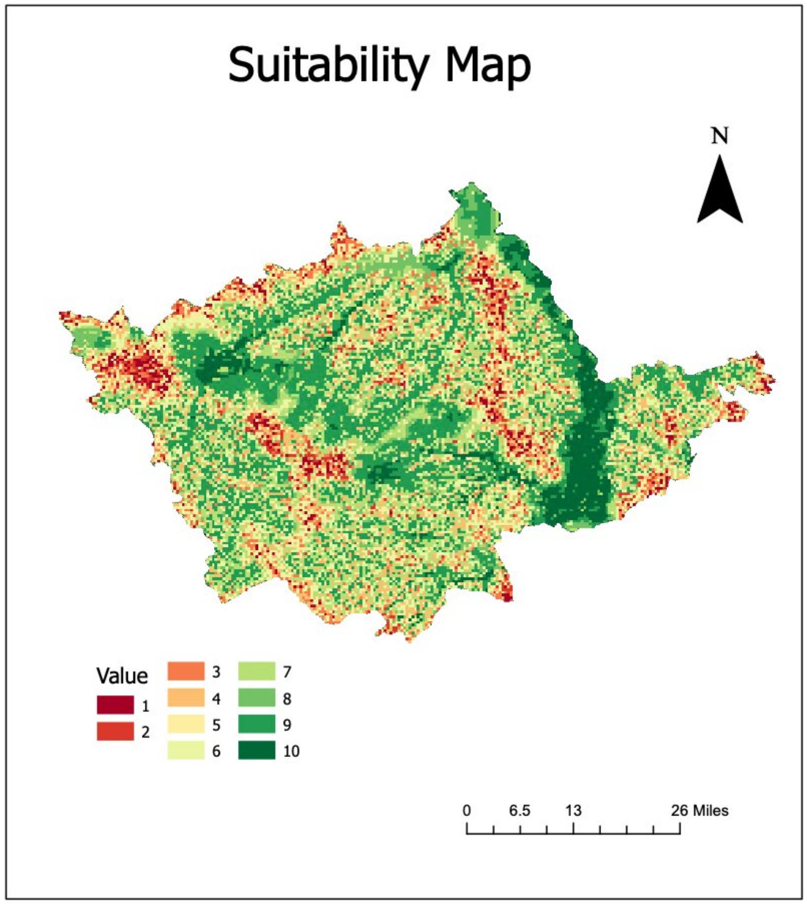
Suitability ranking

Table 2. Suitability ranking table

Criterion	Class	Value	Score

Rainfall (mm)	Use function to describe	>200	9
Slope (%)	Flat	0-2.5	9
	Undulating	2.5-5	8
	Rolling	5-7.5	7
	Hilly	7.5-10	5
	Mountainous	>10	1
Land use	Open shrubland	Medium	6
	Cropland	Very high	9
	Grassland	High	7
	Urban	Very low	1
	Barren	Low	3
Driange network	Inside the buffer zone	High	6-9

	Outside the buffer zone	Low	5
	Away from the buffer zone	Very low	1-3
Soil texture	3722-Loam	High	7
	4328-Clay loam	Very high	9
	4389_Loam	High	8



DISCUSSION

The suitability is shown on the map, while 1 refers to most unsuitable and 10 refers to most suitable. From the map, we can get the result that in the study area 64% lands can meet the requirements for ridge and furrow rainwater harvesting. The modeler chose 10 sites by calculating the average suitability value within the area and took the highest 10. They can be integrated into Five sites, marked in the following map: A & B are middle-east cropland which has abundant rainfall, slight slope and close to the drainage system. There are several advantages: (1) The place has the best water and soil conditions. It means rainwater can be held for a longer time and with higher efficiency. (2) The original croplands allow large scale water saving practices. (3) RWH can strengthen the resistance ability to drought in this important food production base. Especially under the foreseeable climate change that extreme pattern happens more frequently.

C, D & E are existing grasslands but with high potential to harvest if the rainwater can be used in production. This also has several advantages: (1) The increase in cropland can bring a boost in yield. This is very important for a populous country like China. (2) They can be ideal sites for other RWH methods experiments. (3) It allows more flexible land use planning in Haiyuan county, Ningxia.

CONCLUSION

Water scarcity is becoming global issue. For less developed countries like China, the deficient water supply can influence the food security that threaten the daily life of the mass population. To deal with it, rainwater is seen as a reliable source that can be collected and put into production to mitigate water scarcity. Ridge and furrow is one of the widely tested productive rainwater harvesting method. It's a cost-effective way for less developed countries to develop a water-saving agriculture production pattern. This research shows there is a high potential for Haiyuan, Ningxia, China to use ride and furrow in daily production, especially in the east and middle of the county which has relatively superior rainfall and soil conditions for crops.

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