sustainability

MDPI

Article

Evaluation and Clustering Maps of Groundwater Wells in the Red Beds of Chengdu, Sichuan, China

Haijing Zhang [1,2,3], Qingyun Du [1,2,3], Min Yao [4] and Fu Ren [1,2,3,*]

Received: 12 November 2015; Accepted: 12 January 2016; Published: 18 January 2016
Academic Editor: David J. O'Brien

1 School of Resource and Environmental Science, Wuhan University, 129 Luoyu Road, Wuhan 430079, China; zhanghaijing@whu.edu.cn (H.Z.); qydu@whu.edu.cn (Q.D.)
2 Key Laboratory of Geographic Information System, Ministry of Education, Wuhan University, 129 Luoyu Road, Wuhan 430079, China
3 Key Laboratory of Digital Mapping and Land Information Application Engineering, National Administration of Surveying, Mapping and Geo-information, Wuhan University, 129 Luoyu Road, Wuhan 430072, China
4 Chengdu Land and Resource Information Center, 69 Jinxiu West Road, Chengdu 610072, China; clric-ym2007@163.com
* Correspondence: renfu@whu.edu.cn; Tel.: +86-27-6877-8675; Fax: +86-27-6877-8893

Abstract: Since the start of the 21st century, groundwater wells have been placed in red beds to solve the problem of scarce water resources in Southwest China and have rapidly expanded to other areas. By providing examples of cartography in Chengdu and Sichuan, China, and using the locations of groundwater in fractures and pores when monitoring and managing red sandstone and mudstone wells, a series of maps of groundwater wells at different scales in the red beds of Chengdu was obtained. Most of the wells located in red beds are located in Jintang, Dayi, and Qingbaijiang and exhibit different cluster features. The kernel density estimation and spatial cluster analysis classification methods were used based on the Density Based Spatial Clustering of Applications with Noise algorithm (DBSCAN) in three concentrated areas. This method describes the trends of the clustering results and the relationships between the locations of residents and red bed wells. The cartography results show that the groundwater wells in red beds are mainly distributed in hilly areas and partially correspond with the locations of villages and settlements, particularly their geological and topographic factors, which satisfy the maximum requirements of water use and recycling in Southwest China. The irrigation wells located in red beds are not only reliable and efficient but also replace inefficient water resources in the recharge-runoff-discharge groundwater process, which promotes the sustainable development of groundwater resources.

Keywords: groundwater wells in red beds; point clustering; drinking water; irrigation; DBSCAN

1. Introduction

The problem of water shortage is more serious in China than any other nation on Earth, especially in the wide region of Southwest China, where precipitation and terrain limit the economic and sustainable development of cities, such as Chengdu, Chongqing, and Kunming [1,2]. Drilling for water in red bed hills can resolve water scarcity problems for farmers in hilly regions and increase their income while improving the sustainability of agriculture within the country.

Red beds are continental red sediments with regular sedimentary textures and structures and fissures that contain various forms of groundwater. Although red beds [3–6] and the groundwater in red beds [7–9] have been studied, no comprehensive scientific examinations of groundwater wells in red beds have been conducted. Generally, exploiting the groundwater found in red beds is not considered to have great significance because red bed aquifers are relatively poor and difficult to drill through because of their hard rocks.

These wells were drilled to solve the problem of inefficient drinking water supplies for people and livestock for thousands of rural families. As one of the first water-drilling countries (starting more than 5000 years ago), China continues to mainly rely on groundwater in the vast rural and remote areas of China with inefficient water supplies. Based on the irregular distribution of groundwater resources and the presence of fewer aquifers in some areas, the groundwater in bedrock has been extracted, explored, developed, and studied [10–13]. Water drilling projects in red bed hills have been used to investigate groundwater resources and determine the distribution and recharge-runoff-discharge of groundwater in areas with scarce water and red beds.

The earliest groundwater wells in red beds were discovered in the mountain, hill, and plateau areas of Southwest China, including in and around the Sichuan Province [14]. Research regarding groundwater in red beds and drilling for water included geological exploration and spatial analyses, conducted from Sichuan Province to Chongqing, Guizhou, and Yunnan Provinces [15]. More study directions and types of analyses have been involved in related studies in the other fields [16–19]. According to isotope labeling [20] and the recharge-runoff-discharge groundwater process [21], the shallow groundwater in red beds is dominantly derived from meteoric water and is subordinately derived from surface water. In addition, the geomorphological features are believed to be the main factors that control groundwater enrichment.

Because the number of groundwater wells in red beds is increasing, the objectives of this study are to rationalize the development mode, to determine the number of red bed wells, and to ensure that these projects produce long-term benefits. Fang Conggang and Chen Xianwei [22] constructed and implemented groundwater wells to extract water from fractures and pores in red sandstone and mudstone and to monitor and manage information systems during the exploitation of groundwater in red beds. The spatial distribution of the wells could be used for additional spatial analysis and cartography.

Ordinary well maps show the locations of wells, and some 3D models have been used [23,24]. However, few geostatistical and spatial analysis studies have been used to reveal the spatial distributions of factors such as groundwater pollution, aquifer flow, groundwater vulnerability, *etc.* [25]. Geostatistical techniques are spatial and statistical techniques that can be used to assess and present concentrations over space and time [26].

Based on spatial analysis and management, current research provides a map of groundwater wells in red beds as a universally comprehensive professional management series map. This map consists of geographic and geomorphologic-based maps, maps of red bed areas, kernel density grading maps, and DBSCAN cluster maps of well points. These maps can be systematically used to describe the distribution regularities and the number of groundwater well points of red beds in the study area. According to the geostatistical counting and density methods, three districts were chosen in the studied area: high-density and typical districts with various geomorphologic features and groundwater gathering patterns. These districts were evaluated to compare the actual effects of various well characteristics, including the water use efficiency. From the analysis of red beds, well use characteristics, the recharge-runoff-discharge process, and red bed well project-management, sustainable and protective solutions for red bed aquifers are proposed for operating and maintaining wells located in red bed areas.

2. Study Area and Data

Chengdu is located at 30.67°N and 104.06°E in the Sichuan District of China in the Sichuan Basin. The Sichuan Plain in located in the center of Chengdu, and Chengdu is surrounded by the Longmen Mountains on two sides and portions of the Chuanzhong Hills on the northwest. In addition, Chengdu covers an area of approximately 13,277 km^2 (Figure 1a,b). Although water resources are relatively abundant for inland cities, approximately 350,000 people face water scarcity due to poor soil and water conservation.

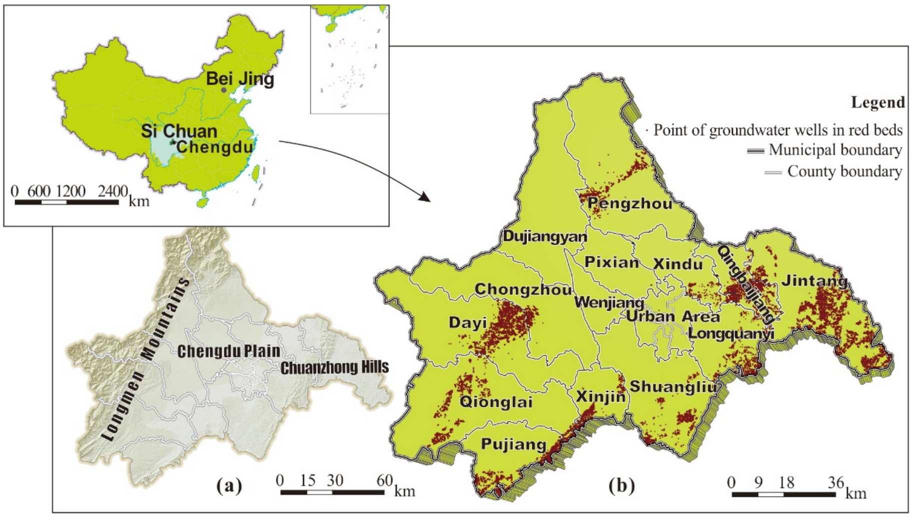


Figure 1. Study area in China: (**a**) geomorphological map; (**b**) administrative map with points showing the locations of groundwater wells in red beds.

2.1. Red Bed Areas

Red beds are widely distributed in Chengdu, especially in the mountain and hill areas on both sides of Chengdu, which mainly consist of red sandstone and mudstone and overlap approximately 75% of water scarcity in the areas. As shown in Figure 2, red bed areas cover approximately 14% of the surface area, which involve 11 districts and more than 4,000,000 people.

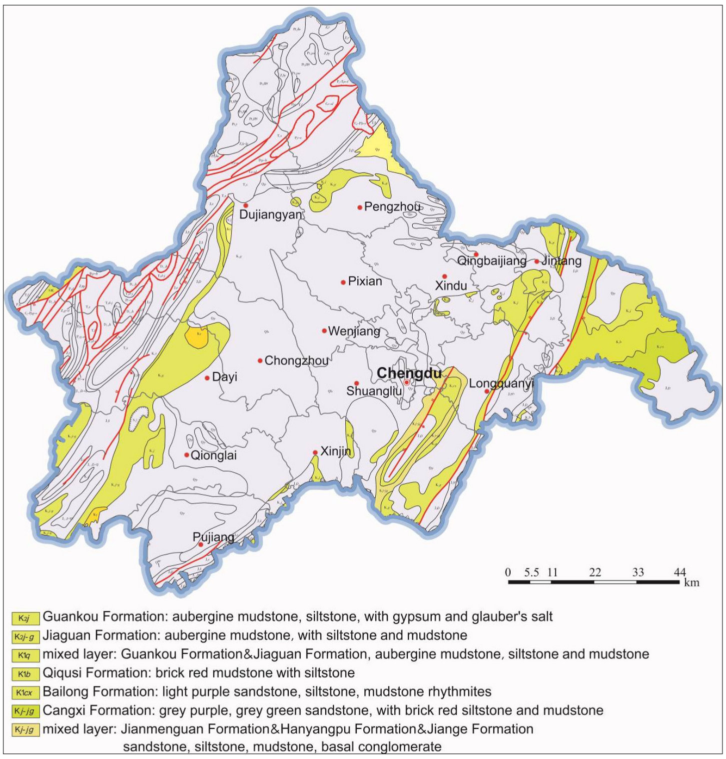


Figure 2. Red bed areas.

2.2. Drinking Water and Irrigation Water

Rural sources of drinking water, including rivers, ponds, reservoirs, wells, streams, *etc.*, are severely threatened, but the protection of these sources is currently insufficient. A number of efforts are required to find water. On the other hand, different levels of pollution make it difficult to ensure the safety of the human drinking water supply. Because of the effects of the broken aquifer on red bed wells and the constrained number of wells due to their cost, most wells were completed after considering multiple factors, such as geology, the locations of residents, the cost of water, and resource availability [27]. However, some of the wells are located in the courtyards of rural households; thus, a complicated relationship exists between man and nature [28,29].

Regarding irrigation water, the water used in traditional irrigation models is mainly from rivers, water conservation, agricultural ponds, and reservoirs in plains; however, it is mainly from wells in water scarcity areas. Although farm irrigation is not necessary, in the 1980s the Ministry of Water Resources issued data about the grain production from irrigated and non-irrigated lands and found that the grain production from irrigated lands was two to four times greater than those of non-irrigated lands, with arid lands benefitting from irrigation more than non-arid lands [30]. Because farmland crops are somewhat replaceable and farmland must meet the living requirements of the residents, the areas that were irrigated in this paper are referred to as irrigation insurance areas. Thus, when some patches of farmland require irrigating, related water resource facilities (including natural water areas and artificial facilities [31]) must meet the irrigation requirements.

2.3. Data Description

2.3.1. Groundwater Wells in Red Beds

More than 60,000 groundwater wells are located in red beds to provide drinking and irrigation water in red bed areas. By November 2010, the monitored and management information system (from 2009), used to manage drilling, maintenance, and ownership problems about the groundwater wells used to obtain water from fractures and pores in red sandstone and mudstone [23], including 33,072 well-points (as shown in Figure 1), have provided experimental data for groundwater wells in red beds. The well points are mainly located around rural households, farmland, foothills, or gullies.

2.3.2. Data from Residential Areas

The data related to the residential areas of each administrative district were mainly obtained from the Chengdu Second State Land Investigation, which began in July 2007 and was completed in 2009. The main objectives of this investigation are to conduct a rural land investigation (*i.e.*, an investigation of the type, location, area, authority, *etc.* of the land), a survey of basic farmland use (*i.e.*, registering and certifying the land and showing the protected farmland on maps showing the actual distribution of land use), and surveys of urban land, cadastral management, and other factors.

2.3.3. DEM and Other Related Areas

This case study was based on three map sheets: medium-scale to large-scale geographical maps; maps from the secondary land survey; and geomorphological maps (DEM). In addition to the groundwater well points in the red beds, the thematic maps were covered by multiple geographical maps, including administrative boundaries, multi-level rivers, lakes and reservoirs, and other related data. The DEM data of Chengdu include the entire urban area and portions of the peripherals and are presented in img format based on the Beijing 54 coordinate system with 6 degrees of zoning and at a scale of 1:50,000.

The "One map" system was set up to meet the needs of new situations and new tasks for soil resource management. The "One map" database includes 13 types of land and resource data, 126 features, 2550 data items, and more than 8.17 million records. The "One map" of the Chengdu database is the core of the land and resource management database, which includes basic geography, remote sensing imaging, rural land surveys, four types of urban land and land use planning surveys, and nine types of thematic data. The "One map" database provides data for supervising mechanisms of land and resources and provides rich and reliable data for this case study.

3. Method

3.1. Data Operation Pattern

The wells management information system, which uses GeoMedia WebMap as a WebGIS platform, supports various forms of data exchange in the B/S model for data collection. Shape files are used here to create a spatial analysis environment in the ArcGIS software (ESRI) and the dxf file from CorelDRAW.

By transforming the geomorphologic and geographical maps, the projection, adjustment, and topology are performed in ArcMap layers and combined with spatial analysis visualizations results to form CorelDRAW layers. The basic data flow of the map operation is presented below (Figure 3).

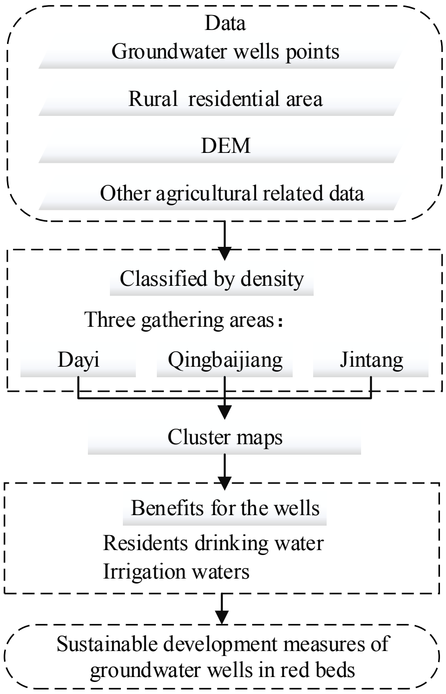


Figure 3. The basic data flow and data frame.

3.2. Classification of Density

The Kernel Density Method is an algorithm used to determine the degree of gathering by calculating the density of the point features around each output raster cell. The Kernel Density Method is chosen here for the cartography of numerous and widely distributed groundwater wells in red beds, because the algorithmic procedure, in which the surface value is highest at the location of the well and decreases with increasing distance from the point (reaching zero at the search radius from the point), agrees with the radiation shape features of the wells. Thus, the kernel density method can be used to simulate the essential density levels of well-points and estimate the distribution features of the groundwater wells in red beds.

The formula used to calculate the default search radius for Kernel Density is:

$$\text{SearchRadius} = 0.9 \times \min\left(SD, \sqrt{\frac{1}{ln\,(2)}} \times D_m\right) \times n^{-0.2} \quad (1)$$

where SD is the standard distance; D_m is the median distance; n is the number of points; and the degree function is:

$$f(x) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{x - X_i}{h}\right) \quad (2)$$

3.3. Cluster Method

For highly aggregating features of the well distribution, the points frequently present a points-overlapping phenomenon during the cartography process, which seriously influences the expression of results in the maps. Thus, the DBSCAN algorithm based on the density of the well locations objectively agrees with the practical situation regarding the distribution and magnitude of wells in red beds.

DBSCAN [32], Density Based Spatial Clustering of Applications with Noise, is an algorithm in which each point *i* in a cluster must contain at least a set of points within a given pre-determined radius *Eps*. DBSCAN implies that the neighborhood density must exceed a user-specified threshold, *MinPts.*

Core point: If the density of a point in space exceeds a certain definite threshold parameter *MinPts*, then this point is called the core point. The number of the adjacent data points in the neighborhood must be greater than four.

Boundary point: If the density of a point in space is less than the threshold value *MinPts*, then the point is called the boundary point. The term boundary point refers to the non-core-point that is included in a certain core point within the neighborhood.

Noise: If C_1, C_2, ... , C_k represents the clusters of the database D, the parameters are *Eps* and *MinPts* and the noise point refers to any set of points in the database D that do not belong to a cluster C_i. Noise is not a boundary or core point.

Each core point and all adjacent core points are placed in a cluster (Figure 4). Clusters with arbitrary shapes can be observed, and outliers can be identified that both require prior specification of the number of clusters. This method focuses on choosing appropriate solutions that reduce the computational cost, and can be used in cases with more outliers and noise points to identify significant structures from maps with various scales without requiring too many tuning parameters from the user.

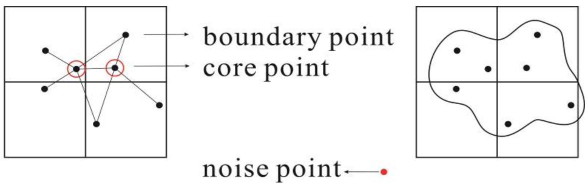


Figure 4. Example of boundary point, core point, and noise point in DBSCAN.

Regarding the two parameters *Eps* and *Minpts*, the reference self-adaption method relies on the degree of well point aggregation instead of a fixed numerical value [33] because of the complicated topography and other actual factors by establishing a distance distribution matrix of $DIST_{n/n}$ as follows:

$$\mathrm{DIST}_{n/n} == \{\mathrm{dist}(i,j) | 1 \leqslant i \leqslant n, 1 \leqslant j \leqslant n\} \quad (3)$$

where n is the number of points in the set. DISTn/n is a symmetric and real matrix with n columns and n rows, and dist(i, j) is the distance between i and j. K groups of parameters (Eps, Minpts) were obtained from the smooth curvature segments by transposing, sorting, drawing, and curve fitting. These parameters were screened by counting the noise points and the only solution (Eps, Minpts) was ascertained. The influences of several factors can be reduced by introducing the self-adaption method for different types of district-concentrated, homogeneous, or scattered areas to understand the effects of the cluster results.

The cluster results revealed the features of groundwater wells in red beds, explained the relative relationships between geographical, geological, and geomorphic characteristics, and reflected the spatial distribution cluster feature subjectively.

4. Results and Discussion

4.1. Map of Density Classification

When using the kernel density estimation to analyze the characteristics of the groundwater wells in red beds according to discrete point processes, three districts emerged with their administrative districts as statistical units: Dayi, Qingbaijiang, and Jintang. The major quality indexes of the areas are presented in Table 1.

Table 1. Basic information for the counties.

County	Number of Well Records	Total Area (km^2)	Red Bed Area (m^2)	Maximum Kernel Density (/km^2)	Mean Kernel Density (/km^2)
Dayi	7224	1283.64	245.12	183	115
Qingbaijiang	3692	378.94	92.63	126	65.7
Jintang	8674	1155.61	596.70	57	38.4
Other regions	<1000	13,276.89	1820.36	–	–

Although different cluster features were embodied in the three regions, the number and degree of clustering were significantly higher than in other regions. From overlaying these areas and the geomorphological factors that can be seen, clusters of red bed wells commonly occur at the junctions between mountainous and hilly areas and plains, and the density trends in other regions correspond with this observation (Figure 5).

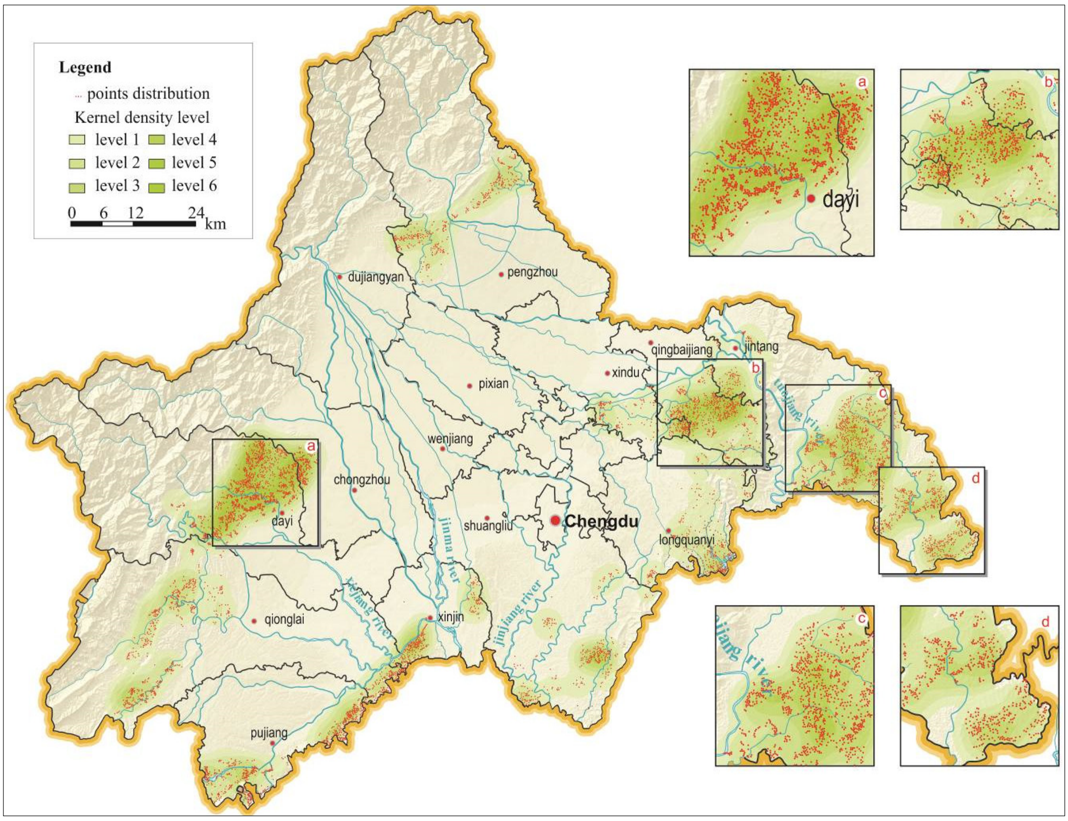


Figure 5. Kernel density level map of groundwater red bed wells.

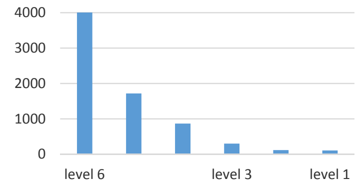
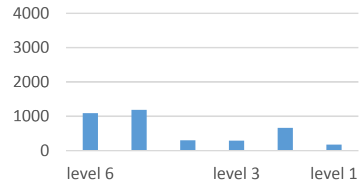
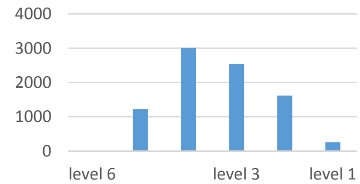
Insights from mapping and confirmation from data analysis indicate that Dayi has the most closely distributed groundwater wells, followed by Qingbaijiang, and that Jintang has the largest number of widely distributed groundwater wells. In the area of Jintang with large hills, few discrepancies have been observed. However, the wells are relatively concentrated in the other two districts, mainly caused by the factor of topography in the mountain-areas.

In this study, three administrative regions are chosen: the western region containing the junction of the mountains and plain (Dayi), the eastern region containing both mountains and plains (Qingbaijiang), and the eastern region containing hills (Jintang). The different distributions of the three regions are linked with the geomorphological features of the region itself and are characteristic of the gathered residents (Table 2).

The Dayi District includes an area where red bed wells are concentrated and the population is sparse in the western mountain area. The region in the eastern plains is vast with relatively abundant water resources, which results in a relatively low water supply cost. The numbers of wells are greatest in the central landforms and densely populated areas among the areas with high densities (level 6). The clusters in the Qingbaijiang District are similar to those in Dayi in Figure 5. However, the density of wells in the Qingbaijiang District is uniformly distributed across the area. This trend is related to an inadequate water supply, uneven rainfall, difficulties in constructing water conservancy facilities, and the mixed terrain containing mountains and plains. The Jintang District is completely different from the other regions, where the distribution of wells is relatively uniform and the medium density area is large. Because many shallow hills and depressions have formed, water is difficult to gather, which is reflected by the residents as well.

Generally, the exploitation and use of red bed wells is slightly affected by external disturbance and is used as an important measure to offset regional water supply defects. This is the main reason why red bed wells are widely popularized in rural settlements in red bed areas that lack water resources.

Table 2. Basic county information.

County	Residential Area Distribution Features	Geomorphological Characteristics	Basic Distribution Characteristics of Red Bed Wells	Number of Wells Distributed Across Six Levels
Dayi	centralized distribution, high aggregation	mountain and plains regions, respectively; more valleys and depressions	dense concentrations in some residential areas, few in some areas, evenly distributed	
Qingbaijiang	overall centralized distribution, partially homogeneous in rural areas, relatively high aggregation	mixed mountain and plain region; partial valleys and hills	widely distributed, related gathering	
Jintang	Evenly distributed, low aggregation	hilly region; depressions and valleys	widely and evenly distributed	

4.2. Spatial Clustering Analysis

Density classifications describe the cluster level, while the cluster results combining with the thematic maps detect the trends and relationships of the distribution of groundwater wells and rural residents. These classifications indicate the cluster process and significance by estimating the homologous neighborhood size in DBSCAN as follows.

Generally, despite the various scales of the villages in the rural areas of China, neighborhood characteristics exist. Thus, delimiting the numeric value as the neighborhood radius in DBSCAN can meet the dispersion law when no noise or outlier points exist within the neighborhood radius of any cluster point. In this case, the set of points appears as one cluster for the same settlement villages or towns. In either of the clustering results, using two standard deviation ellipses would contain and cover approximately 95% (or more) of the points and present the measurement and the orientation distribution (Figures 6–8).

The clustering process is parsed with a Java program, which indicated that the clustering effects were significantly different. In addition, the agglomeration level in Dayi is relatively high, while that in Jintang appears spatially homogeneous, as shown in Table 3.

Table 3. Statistical cluster results.

	Total Number	Cluster Radius (m)	DBSCAN	
			Cluster Count	Outlier Points
Dayi	7224	319.47	208	245
Qingbaijiang	3692	218.79	65	82
Jintang	8674	538.88	40	37

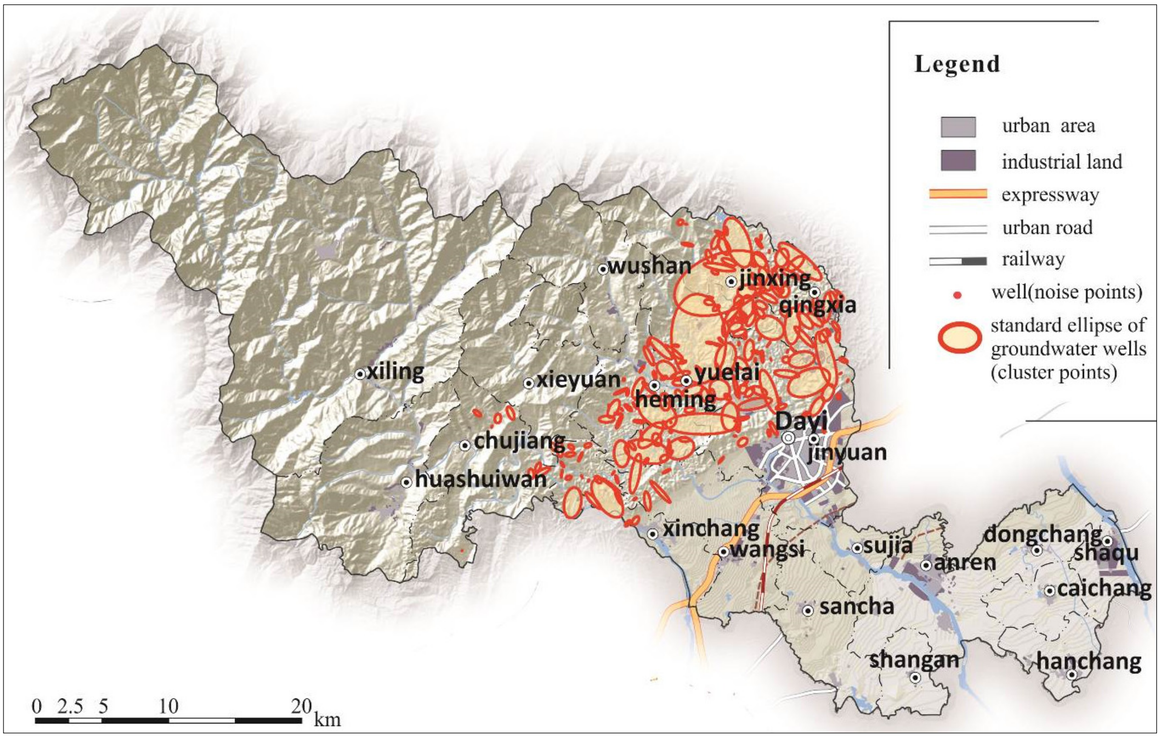


Figure 6. Cluster map of Dayi. The red bed areas of Dayi are limited (with various geomorphological and highly gathering resident areas), the cluster radius is small and the cluster count is large. In addition, the well distribution trend along the geomorphic unit is obvious.

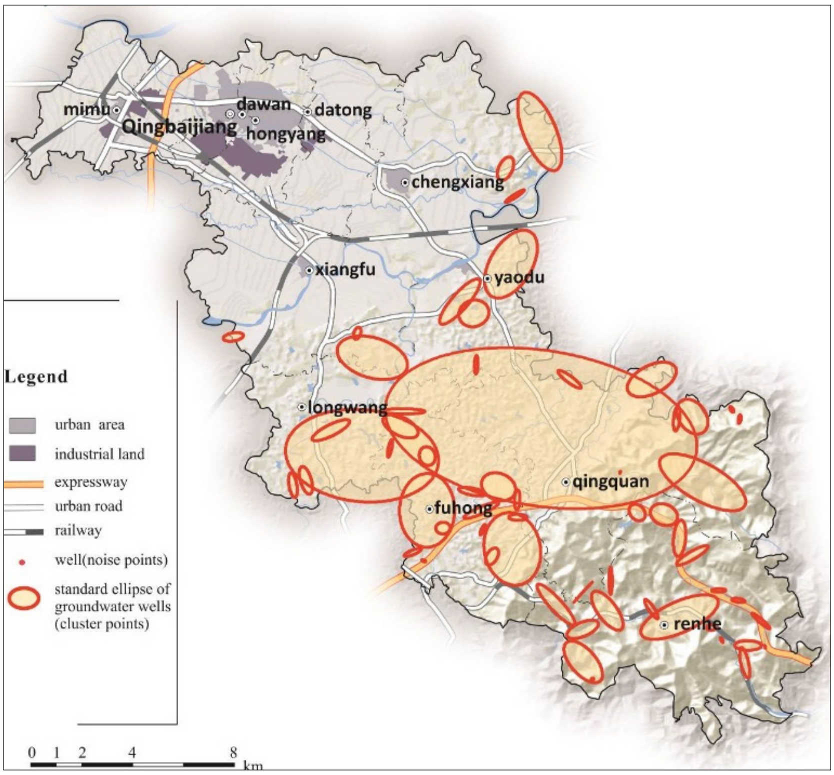


Figure 7. Cluster map of Qingbaijiang. The district includes complex and mixed situations in which the wells gather in regions with low hills and have a narrow shape in other mountainous regions.

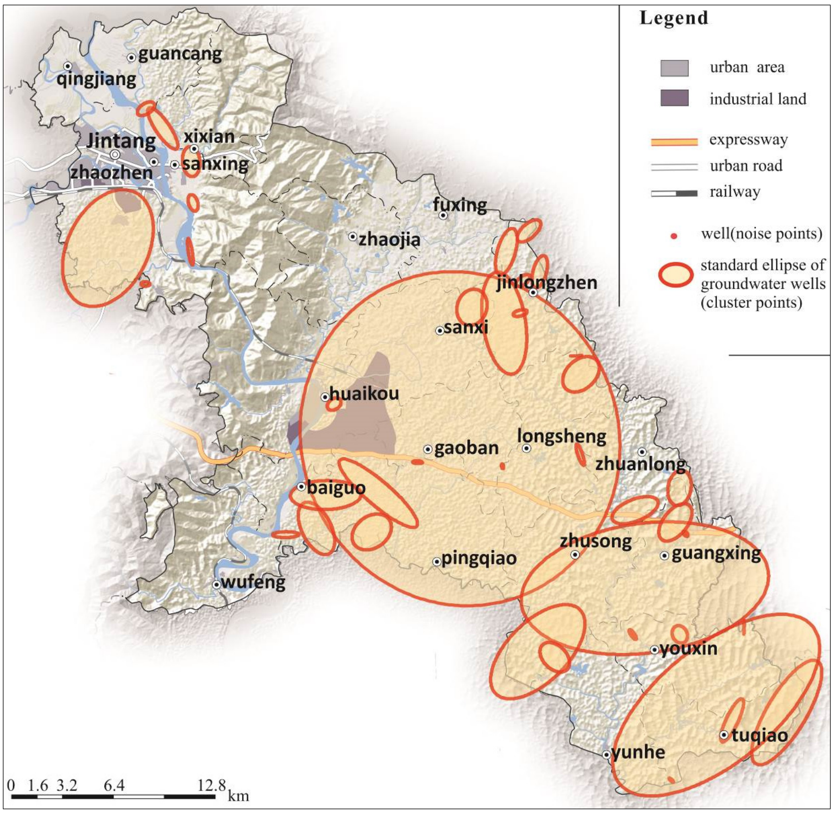


Figure 8. Cluster map of Jintang. The district shows a distinct situation. The wells are evenly distributed in the hill region.

4.3. Benefits for Placing Wells in Red Beds

4.3.1. Resident Drinking Water

Solving drinking water problems in areas with water scarcity problems is a primary task of water drilling projects in red beds. In red bed areas, the locations of wells are partly determined by topography, with most wells positioned near residential areas to reduce the distance required to fetch water. The water fetching distances from rural residential points and their nearest water source (original fetching water points) and wells (present fetching water points) were calculated and compared with those of other areas.

The results indicate that the effects of wells in red beds on reducing the daily cost of fetching water varies in different regions. Especially in Jintang, the influence on the cost reduction of drilling water daily is obvious. Generally, water-drilling projects in red beds can reduce costs by 40% or more, or by more than 80% in areas with multiple wells. These results show the advantages of red beds wells, even near or above the extent in non-scarcity areas.

As mentioned above, the optimum scheme for drilling water for residents is to allocate one well for each rural family in each yard. However, this scheme is not always operable because of the well-drilling locations affected by external disturbance. Therefore, to ensure that the wells can be used properly, some of them are exploited in the highest efficiency areas in the recharge-runoff-discharge process based on proximity. In addition, other wells are shared among several families, resulting in relatively complex water intake. Due to differences in geomorphology and the concentrations of residents, the specific circumstances of the three areas are not always the same. However, the overall results of drilling water can meet the principle of proximity.

To analyze the relative relationships between the locations of the rural residents and the wells, a series of maps were made by clustering results. Each cluster indicated the topotaxy and the distance between the residential areas and well points through the introduction of improved weather graphs of the wind rose plot. The radius of the central round expressed the counts of the well points inside the residential areas, and the "rose petals" expressed the direction and the distance of the nearest well point from each residential area. The distance was expressed by the "near" tool in the ArcMAP toolbox.

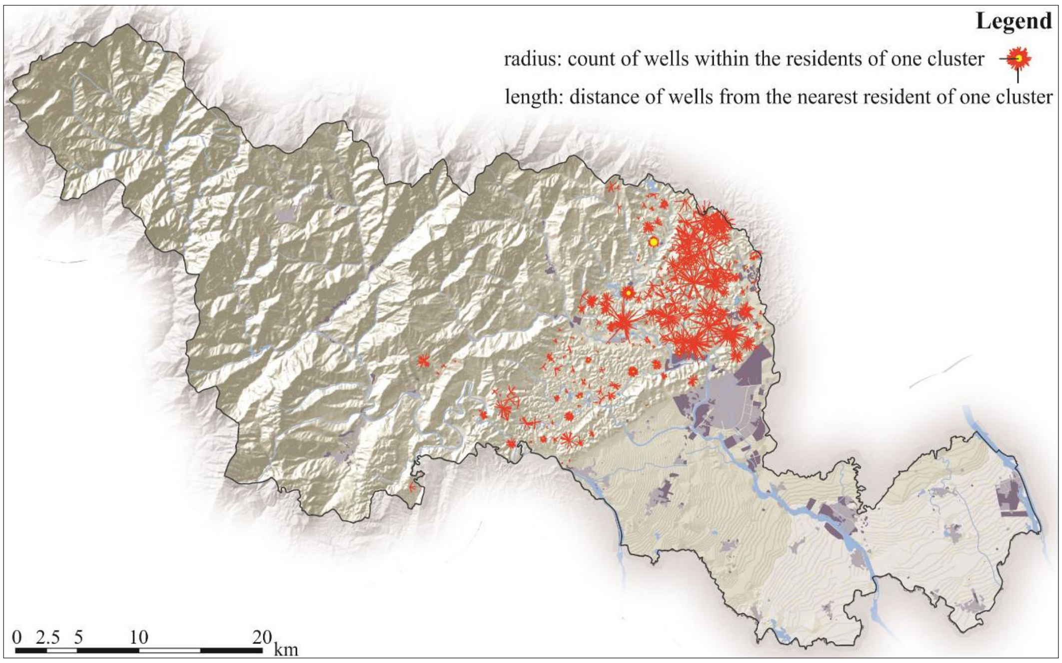


Figure 9. Relative relationships between red bed wells and residential areas in a wind rose plot (Dayi).

In Dayi County, wells rarely appear inside the areas for rural residents, mainly because of the complex topography and the small scale of the rural settlements at these locations (Figure 9). Generally, the distances between the locations of the rural residents and wells in red bed areas are much shorter, and the distances traveled to drill water are short in the most southwestern region of the study area. In the northeast region, the water-drilling mode appears random. This is somewhat related to the results of clustering and partially occurs because of its proximity to urban areas and the effects of various factors on the wells. Therefore, the operation of wells in this small area is various and complex.

Regarding the clustering results in the Qingbaijiang District, the locations of rural wells and residents are tightly related. Most rural wells meet the requirements of drilling water nearby. Rights and liabilities regarding wells are distinct, and the exploitation, management, and maintenance of red bed wells perform in a normal status (Figure 10).

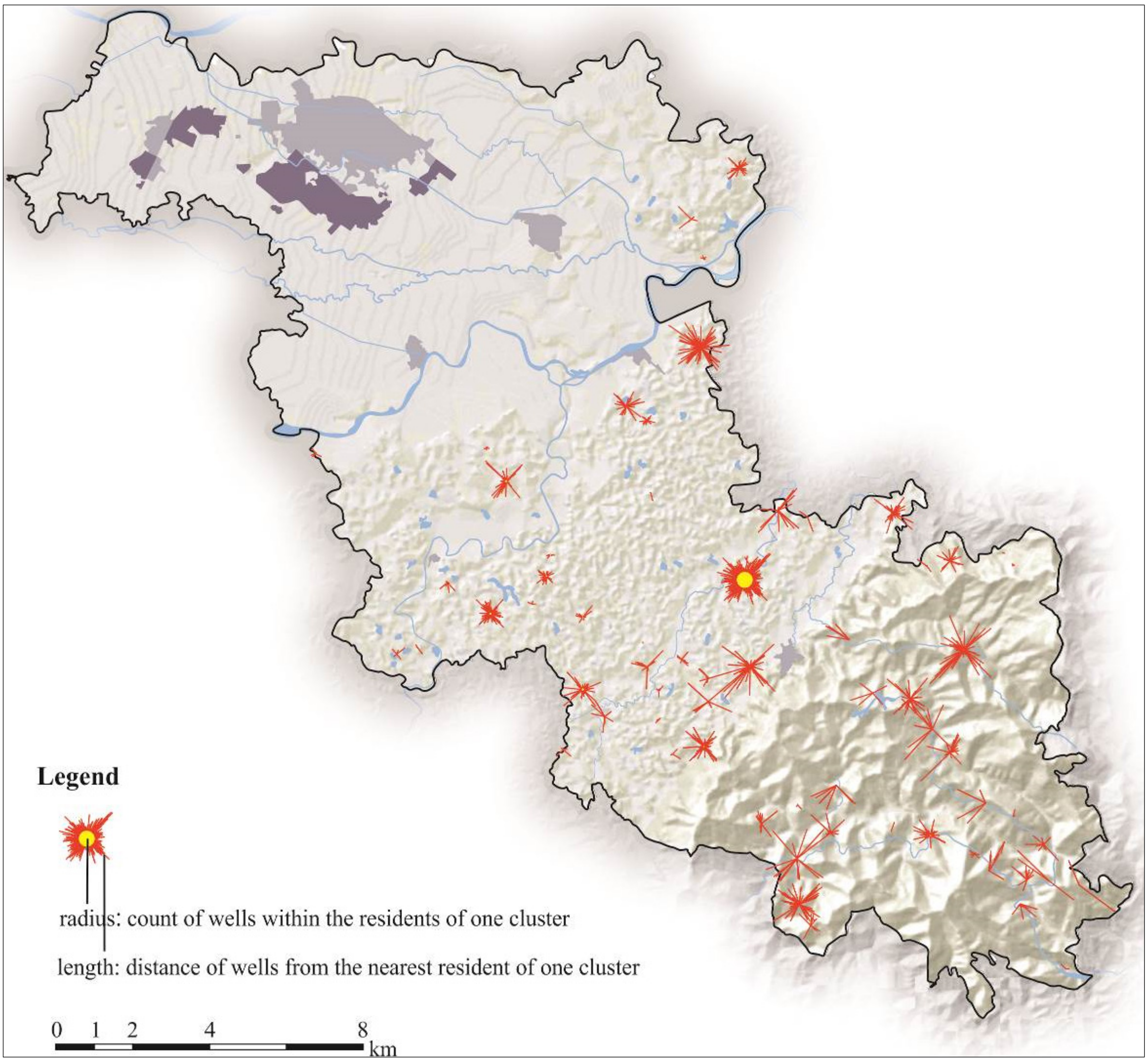


Figure 10. Relative relationships between red bed wells and residential areas in a wind rose plot (Qingbaijiang).

In the Qingbaijiang District, several factors, such as topography, scale, clustering of rural settlements, *etc.* are universal. These factors can represent the region features of vast rural areas in Southwest China. The exploitation and usage of red bed wells mainly aim to solve the difficult problem of supplying drinking water to residents and livestock in rural areas. Low-cost, highly efficient, and convenient solutions are presented to solve the problem of obtaining drinking water for residents in their daily lives.

The regional features in the Jintang District are comparatively special. In hilly areas, the contact ratio of wells and residents is very high (Figure 11). Well sharing is relatively rare due to the low degree of settlement. Wells are mainly located in the yards of rural families, which makes water intake much more convenient.

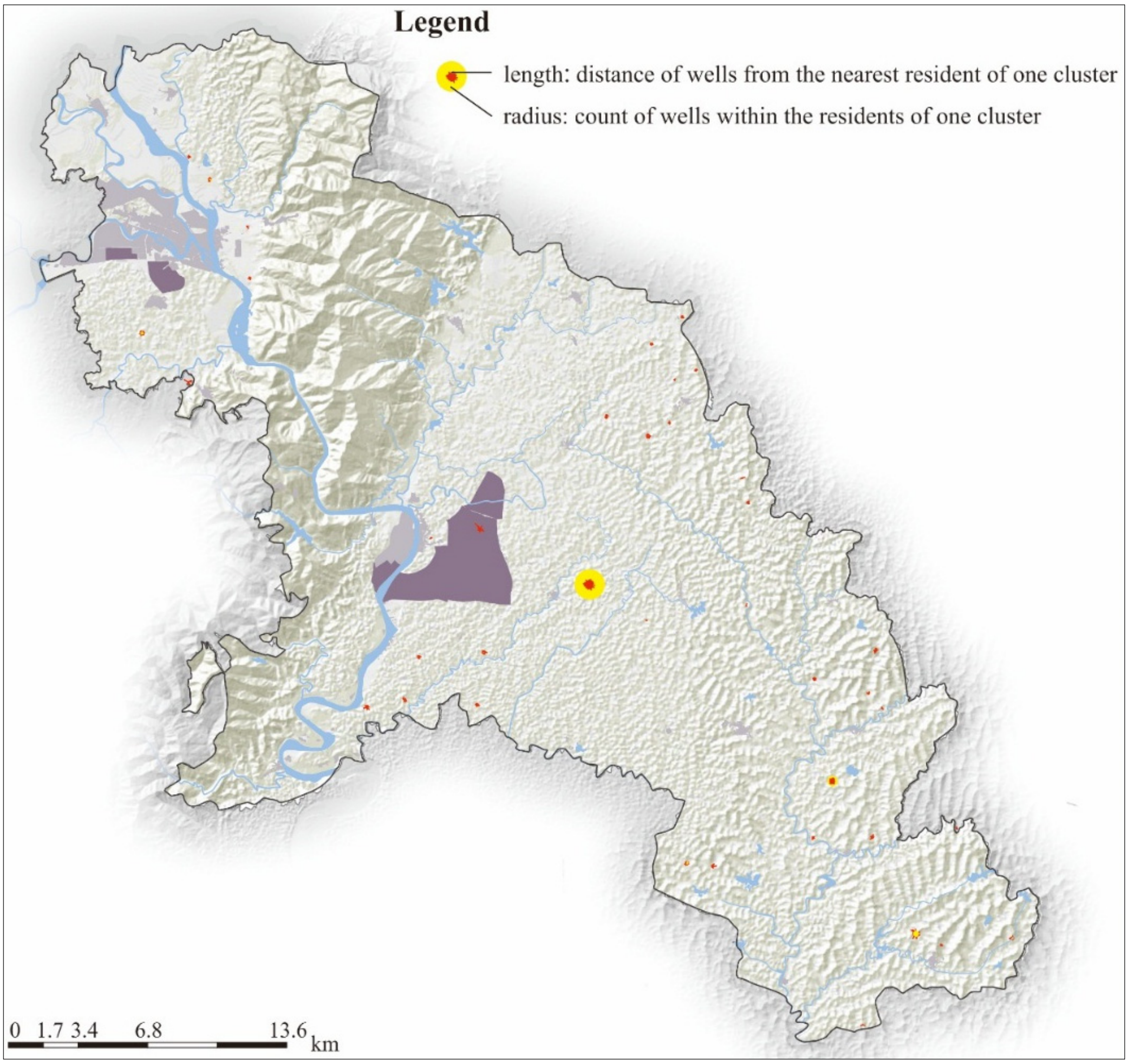


Figure 11. Relative relationships between red bed wells and residential areas in a wind rose plot (Jintang).

Generally, rural wells and resident settlements are closely related in Jintang because nearby water-intake sources are the best. However, when analyzing the factors combined with the actual topography, shallow hills decrease the effects of recharge-runoff-discharge on red bed wells. As a result, the amount of water in the wells is not sufficient for proper operation during the dry season. Thus, it is sustainable to fetch water in the Qingbaijiang District and the situation mentioned above is universal across the vast rural areas in Southwest China. Moreover, based on an analysis of the Dayi District, the wells in partial regions are overly intensive, which causes a type of exhaustive waste exploitation. Therefore, one objective is to control the general intake of water from red bed wells to maintain rational exploitation.

4.3.2. Irrigation Waters

Although red bed wells are mainly used to solve the problem of inadequate drinking water for humans and animals in rural areas with few water resources, their use for irrigation cannot be ignored. Generally, red bed areas and farmlands significantly overlap, as shown in Figure 12. Red bed wells are important for irrigation, especially in farmland areas near rural settlements, where farmers may plant larger areas of crops with irrigation instead of some areas of crops without irrigation. As such, actions have been taken by farmers to exploit wells and optimize well locations to remedy deficiencies in water conservation and farmland facilities in hilly areas.

More importantly, irrigation wells in red bed areas are linked with the recharge-runoff-discharge groundwater process in fractures and pores in red sandstone and mudstone. Because the red soils in the Sichuan Basin have poor water storage abilities, well irrigation reinforces recharge-runoff-discharge in the sustainable development of red bed wells.

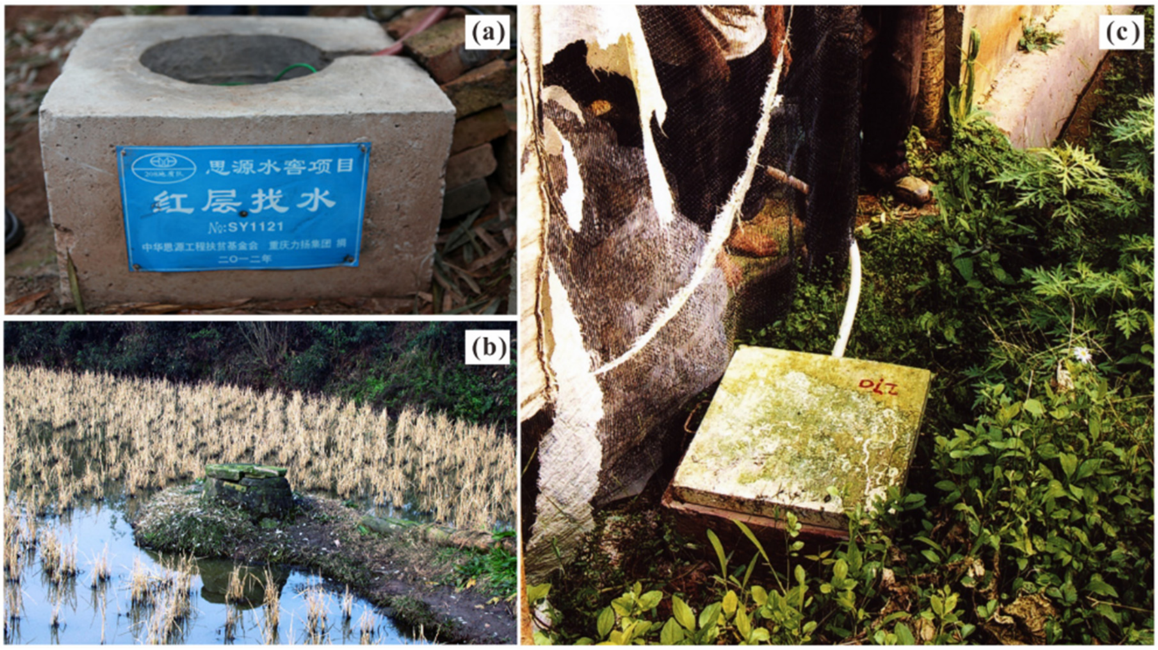


Figure 12. Photos of red bed wells: (**a**) Water drilling in a red bed project; (**b**) a red bed well used for irrigation; (**c**) a red bed well used for drinking.

Regarding distribution, the areas with red bed wells used for irrigation where water is scarce refer to buffer areas of wells. Thus, by comparing water conservation and agricultural land facilities in other areas, the influence areas can be set by using gradually decreasing buffer distances of 50 m to 1000 m. The concrete distribution features are different in the three districts as follows (Figures 13–15, Tables 4–7).

Table 4. Comparison of fetching water distances in different situations.

Fetching Water Distance	Red Bed Areas		Other Areas
	To Wells (m)	To Waters (m)	To Waters (m)
Dayi	290	515	119
Jintang	35	256	230
Qingbaijiang	181	430	368

Dayi

In the red bed areas of Dayi County, the buffer areas of the red bed wells and water conservancy are nearly the same, especially in the medium range of 200 m, and the wells have a larger radiation area than the water conservation facilities. This result shows that the insurance effects are not very different between water conservation and well irrigation. Because the buffer areas of agricultural facilities are much smaller than the other two areas, some limitations exist regarding irrigation. In addition, universality and convenience are advantages of red bed wells. According to the thematic map in Figure 13, irrigation in the plain area is very dense but has a significantly reduced effect in mountain areas. In addition, the irrigation insurance region of the red bed wells and the regions of water conservancy are relatively complementary (in the northwest region of the red bed areas).

Table 5. Dayi.

Effective Irrigation Distance	Red Bed Areas (245.12 km^2)			Other Areas (1038.52 km^2)	
	Well Buffers (km^2)	Water Conservancy Buffer (km^2)	Agricultural Land Facility Buffer (km^2)	Water Conservancy Buffer (km^2)	Agricultural Land Facility Buffer (km^2)
50 m	24.98	27.09	1.10	164.99	5.44
100 m	61.37	51.94	2.03	252.52	9.67
200 m	125.37	95.24	4.63	317.66	20.75
300 m	170.12	129.63	8.14	347.88	34.88
500 m	226.56	173.71	17.98	388.71	70.66
1000 m	313.18	225.56	55.56	469.82	178.91

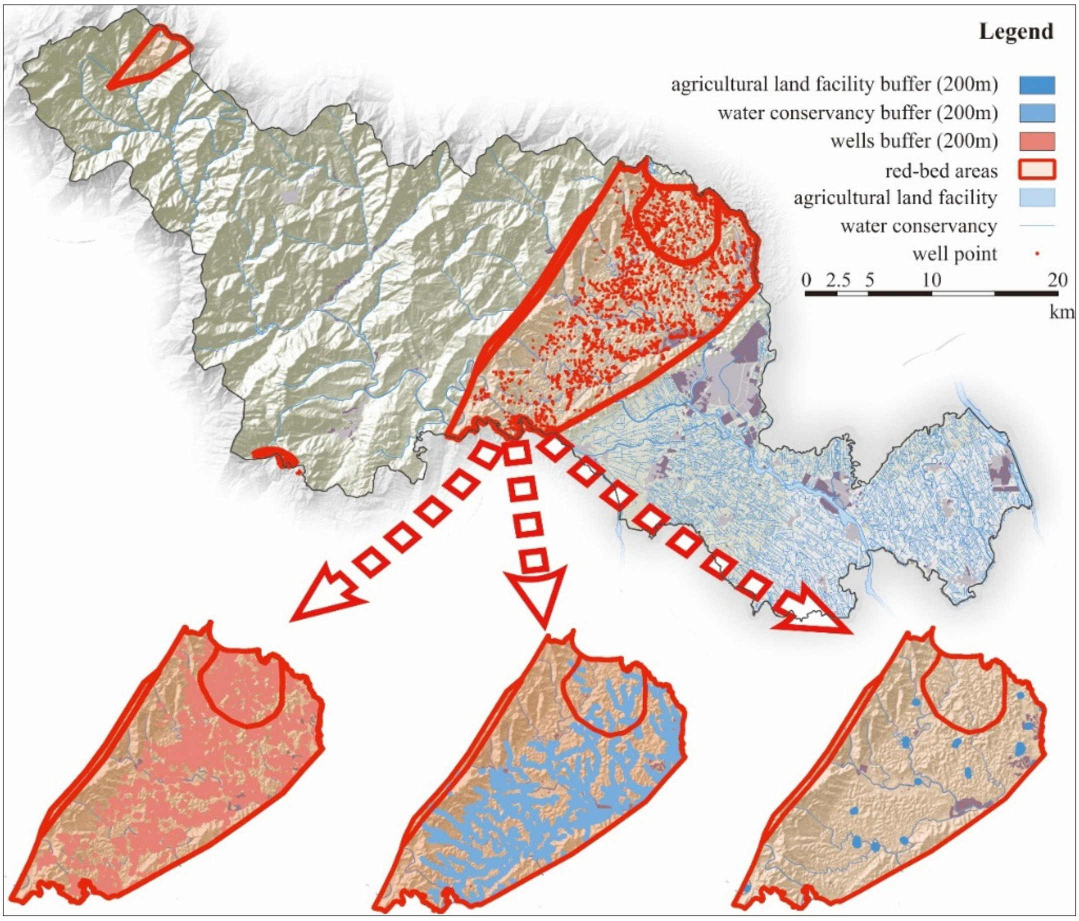


Figure 13. Relative relationships between the wells and other water conservancy and agricultural land facilities.

Qingbaijiang

The Qingbaijiang District is a small area with a typical hybrid landscape and a handful of water conservancy facilities. The shortage of water resources for irrigation is very severe in this area. Thus, the red bed wells in the Qingbaijiang District are widely used and promoted, especially in red bed areas with water scarcity, where the use of irrigation wells is much greater than those concerns for water conservation and agricultural sustainability over wide areas. Nearly all of these areas use wells for irrigation.

Table 6. Qingbaijiang.

Effective Irrigation Distance	Red Beds Areas (92.63 km^2)		Other Areas (288.36 km^2)
	Well Buffers (km^2)	Water Conservancy and Agricultural Land Facility Buffer (km^2)	Water Conservancy and Agricultural Land Facility Buffer (km^2)
50 m	9.87	6.53	28.26
100 m	25.65	11.53	48.65
200 m	52.70	21.06	87.02
300 m	68.19	30.09	123.62
500 m	86.35	47.07	192.21
1000 m	123.37	84.74	323.47

* For different data specifications, combine the water conservancy and agricultural facility data.

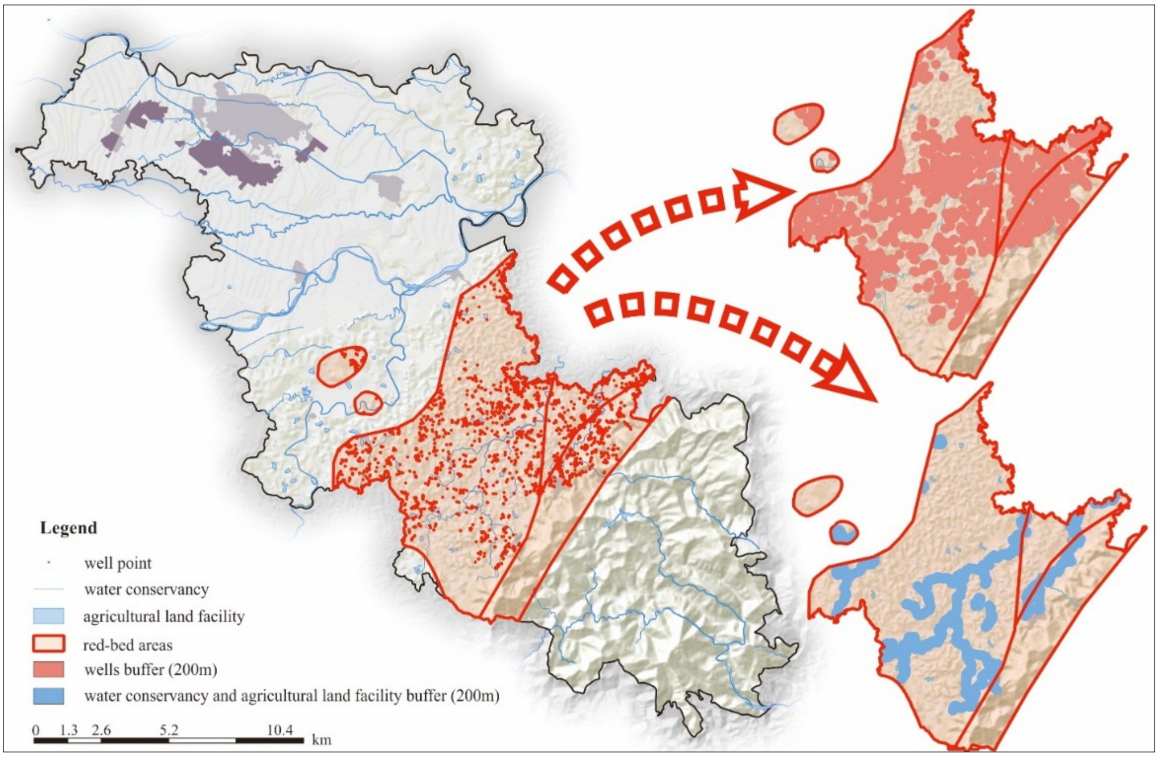


Figure 14. Relative relationships between the wells and other water conservancy and agricultural land facilities.

Qingbaijiang is a typical county with a water scarcity problem, and represents other such counties widely distributed in Southwest China. These counties are mostly located in a complicated topographical environment, and usually have uneven precipitation and frequent droughts and floods (mainly droughts) that result in a major reduction in crop yields. The use of red bed wells counteracts extreme situations with unfavorable conditions, and provides an operable measure for sustainable agricultural development in these areas.

Jintang

The use of wells in the Jintang area had a similar effect, but Jintang includes a large area with low hills and a uniform altitude distribution with further distance to the plain and developed regions. Thus, water conservation projects in this area are difficult to implement. These factors all result in a large area with water scarcity, where red bed wells are the main source of water. Although the wells are distributed evenly, it may be difficult to protect irrigation water. In this area, farmers should select dry crops, especially self-sufficient ones.

Table 7. Jintang.

Effective Irrigation Distance	Red Beds Areas (596.69 km^2)		Other Areas (558.40 km^2)
	Well Buffers (km^2)	Water Conservancy and Agricultural Land Facility Buffer (km^2)	Water Conservancy and Agricultural Land Facility Buffer (km^2)
50 m	27.28	54.15	57.49
100 m	72.30	84.54	95.23
200 m	157.42	145.31	169.98
300 m	218.37	206.50	243.87
500 m	300.7	328.52	390.89
1000 m	440.89	580.83	717.66

* For different data specifications, combine the water conservancy and agricultural facility data.

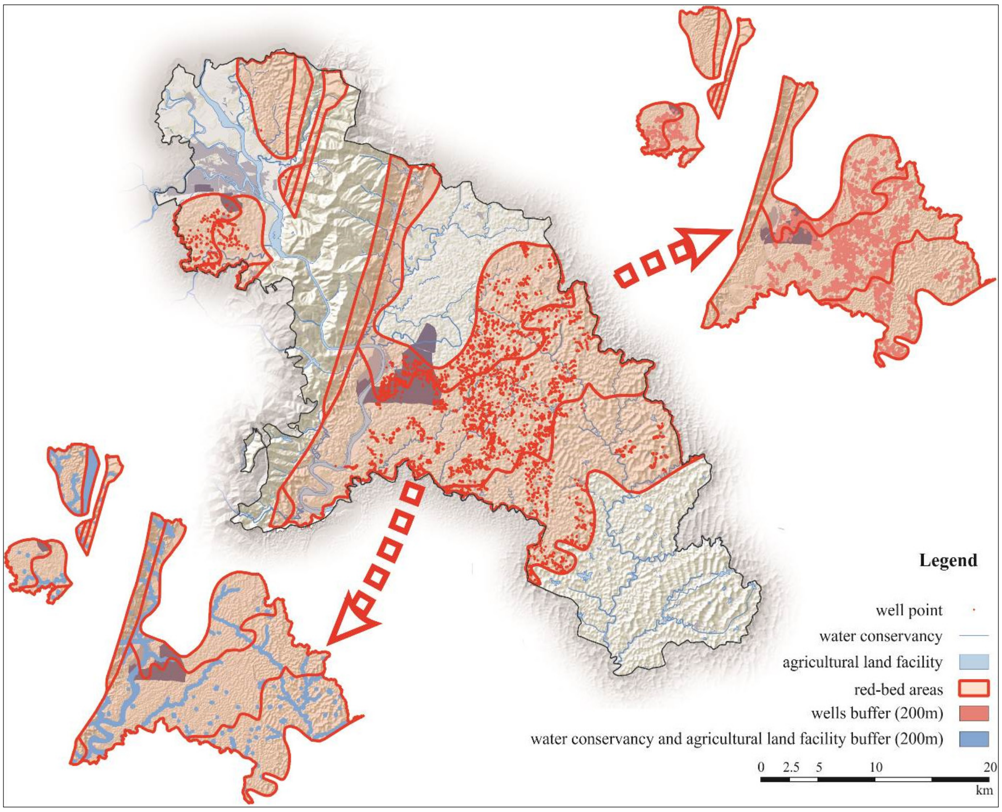


Figure 15. Relative relationships between the wells and other water conservancy and agricultural land facilities.

Generally, the calculation results for the three districts all showed that the strong influences of red bed areas reach those of other areas. The red bed wells have better effects than general water conservation and agricultural land facilities for the terrain in areas with scarce water availability, which points towards the objective selection of factors. Thus, the red bed wells have obvious insurance functions in irrigation, complement water conservancy and agricultural land facility in some areas (e.g., northeast Dayi), and effectively and directly solve irrigation problems. Although no direct water content information was used to ensure irrigation, the development of water drilling projects in red beds can prove the effects of irrigation on local food crops and prevent drought and flood damage while ensuring the sustainability of water resources in the recharge-runoff-discharge process.

5. Conclusions

Red bed wells have been used to solve the difficult problem of insufficient drinking water supply for residents and livestock in rural areas in Southwest China, and are widely distributed in areas with water scarcity problems. In Chengdu, which is located in the Sichuan Province, red bed wells are concentrated in Jintang, Dayi, and Qingbaijiang according to various provincial characteristics of natural conditions and resident gathering areas. Generally, groundwater wells are distributed based on settlement clustering, in contrast with groundwater wells in red beds that are not distributed according to settlements because they follow the fractures and pores of the red sandstone and mudstone. Thus, the concept of the neighborhood in the DBSCAN clustering method correctly describes the settled villages. According to the kernel density grading results, the cluster shapes in the three districts and the relationships between the geographical elements and residential areas, a series of maps were made, including the Red Beds Wells Kernel Density Grading Map of Chengdu and the Red Beds Wells Cluster Maps of Dayi, Qingbaijiang, and Jintang.

From the perspective of the drinking water of residents, water-drilling projects and operation in red beds can decrease the distance required to fetch water and reduce costs by more than 80% in areas where wells are concentrated, which indicates the obvious advantages of red bed wells. Compared with the water conservation and agricultural land infrastructures used in other areas, the wells used for irrigation significantly affect daily activities in areas with water scarcity problems because the red bed wells are reliable and efficient at alleviating water deficiencies at conservation and farmland facilities, promoting the sustainability of water resources in recharge-runoff-discharge processes, and providing countermeasures against natural drought and flood disasters.

Generally, differences were observed in the use of red bed wells between the three districts with various landforms. When comprehensively considering the economic, social, and environmental factors, the development and use of red bed wells should be adjusted to local conditions. In areas with mountains or mountains and hills, red bed wells are the main source of water because other drilling methods for obtaining water are impracticable. Thus, it is important to ensure that red bed wells are not exploited. In these areas, the recharge, runoff, and discharge of wells and local precipitation can be ensured in addition to water yield and water quality. In areas with plains and lower hills, wells are exploited to provide convenient drinking water and irrigation. The characteristics of the distribution of the fissure water in red beds results in a water resource that is partly inefficient in the recharge-runoff-discharge groundwater process. In addition, drilling for water in red beds reinforces the links between recharge, runoff, and discharge in the sustainable development of red bed wells. However, some rich aquifers in some areas are easily overexploited, which leads to exhaustion or improper local distribution. Thus, for practical work, controlling the overuse of red bed wells remains an important problem.

Maps of groundwater wells in red beds have different themes and were created to perform different functions, particularly regarding the management process in which details and the overall situations are considered. Analogous to the multistage tiles technology in GIS, different clustering methods could be used to apply the clustering results of multistage scales to manage groundwater wells in red beds to monitor, analyze, and manage projects. For example, an agglomerative hierarchical clustering method could be used for the wells distribution management in small areas like a township or village, relative to large-scale management and discrete well points. Regarding sustainable development, continuously updating and accumulating more attributes information of the states, water levels, and water content of red bed wells, and using spatial and hydrologic analyses could provide scientific and objective results that could be applied to the aquifer distribution and the change features, and then used to monitor the aquifer effectively to rationally allocate the water resources by some administrative measures.

Acknowledgments: This study was supported by the National Natural Science Foundation of China (Project No. 41271455 and 41371427). The authors would like to thank Xueling Wu from China University of Geosciences (Wuhan, China) for her valuable suggestions.

Author Contributions: Haijing Zhang, Qingyun Du, Min Yao, and Fu Ren worked together on this project. Haijing Zhang conducted the main experiments in the study areas, provided some analyses of the red bed areas, and used cartography to describe the results. Qingyun Du improved the ideas proposed by Haijing Zhang, guided the experiments, and organized the content of the paper. Min Yao collected some experimental data and supported related work. Fu Ren provided guidance based on the literature and proposed the study.

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

References

1. Wu, C.-F.; Déry, S.; Wu, W.-C. A review of water resources utilization and protection in Southwest China. *Sci. Cold Arid Reg.* **2015**, *7*, 736–746.
2. Yu, X.; Geng, Y.; Heck, P.; Xue, B. A review of China's rural water management. *Sustainability* **2015**, *7*, 5773–5792. [CrossRef]
3. Cohee, G.V. Geologic history of the Michigan basin. *Wash. Acad. Sci.* **1965**, *55*, 211–223.
4. Shaffer, B.L. Palynology and geology of newly discovered Jurassic sediments in the Michigan basin (Abstract). *Geol. Soc. Am.* **1968**, *115*, 376–377.
5. Shaffer, B.L. Palynology of Michigan "Red Beds". Ph.D. Thesis, Michigan State University, East Lansing, MI, USA, 1969.
6. Westjohn, D.B.; Weaver, T.L.; Zacharias, K.F. *Hydrogeology of Pleistocene Glacial Deposits and Jurassic "Red Beds" in the Central Lower Peninsula of Michigan. Water-Resources Investigations Report 93–4152*; U.S. Department of the Interior, U.S. Geological Survey: Reston, VA, USA, 1994; p. 14.
7. Simpson, L.C.; Harrington, J.M.; Johnson, K.S. Hydrogeology of the Garber-Wellington aquifer in Oklahoma City, Oklahoma, USA. *Int. Contrib. Hydrogeol.* **1999**, *21*, 245–250.
8. Leybourne, M.I.; Peter, J.M.; Johannesson, K.H.; Boyle, D.R. The lake St. Martin bolide has a big impact on groundwater fluoride concentrations. *Geology* **2008**, *36*, 115–118. [CrossRef]
9. Benison, K.C.; Knapp, J.P.; Dannenhoffer, J.M. The Pennsylvanian Pewamo formation and associated Haybridge strata: Toward the Resolution of the Jurassic Ionia Red Bed Problem in the Michigan Basin, U.S.A. *J. Sediment. Res.* **2011**, *81*, 459–478. [CrossRef]
10. Liu, G.-Y. *Groundwater in Bedrock*; Geological Publishing House: Beijing, China, 1979. (In Chinese)
11. China Geological Survey. *Groundwater Exploration in the Arid and Semiarid Areas in China*; Geological Publishing House: Beijing, China, 2003. (In Chinese).
12. China Geological Survey. *Groundwater Exploration for Drinking in the Water-Shortage Areas of the Western China*; Geological Publishing House: Beijing, China, 2006. (In Chinese).
13. Zhang, T.-S.; Chen, X.-H.; Jiang, Z.-Y.; Lan, G.-Z. Occurrence of groundwater and its influence factors in Red Bed region, Sichuan basin. A case study of Nanchong City. *Acta Geol. Sichuan* **2005**. [CrossRef]
14. Yong, Z. The prospects for underground water exploitation in red bed hill region in Sichuan basin. *Acta Geol. Sichuan* **2000**, *20*, 262–264.
15. Wu, X.-G.; Zhu, C.-L.; Yu, S.-Y.; Li, J.-D. Discussion on water detection method for rock strata with poor-water in red beds of mid-Yunnan area. *Subgr. Eng.* **2012**, *2*, 134–137.
16. Zhang, M.; Yin, Y.; Huang, B. Mechanisms of rainfall-induced landslides in gently inclined red beds in the eastern Sichuan basin, SW China. *Landslides* **2015**, *12*, 973–983. [CrossRef]
17. Li, S. Analysis research of chemical feature of shallow underground water in Red Bed Land in Hebei. *Int. J. Digit. Content Technol. Appl.* **2013**, *7*, 341–347.

18. Samanoudi, E.; Ebid, G.-S.; Rofail, N.-N.; Ismail, Y.-L.; Hawash, S.-A.-F. Assessment of groundwater resources in northeastern Sinai Peninsula constrained by mathematical modeling techniques. *J. Earth Sci. Eng.* **2013**, *1*, 23–34.
19. Sorlini, S.; Palazzini, D.; Sieliechi, J.; Ngassoum, M. Assessment of physical-chemical drinking water quality in the Logone valley (Chad-Cameroon). *Sustainability* **2013**, *5*, 3060–3076. [CrossRef]
20. Chen, Q.-G.; Zheng, W.-M.; Chang, X.-J. An approach to the relationship between recharge, runoff and drainage of groundwater in the typical red beds: An Example from Rongchang in Chongqing. *Sediment. Geol. Tethyan Geol.* **2011**, *31*, 107–112.
21. Erickson, T.-O.; Stefan, H.-G. Natural groundwater recharge response to urbanization: Vermillion River Watershed, Minnesota. *J. Water Resour. Plan. Manag.* **2014**, *135*, 512–520. [CrossRef]
22. Fang, C.-G.; Chen, X.-W.; Liu, X.-C.; Chen, T. Construction and implementation of fracture-pore groundwater well in red sandstone and mudstone monitoring and management information system. *Sci. Technol. Manag. Land Resour.* **2010**, *6*, 119–124.
23. Venteris, E.-R. 3-D modeling of glacial stratigraphy using public water well data, geologic interpretation, and geostatistics. *Three-Dimens. Geol. Mapp. Groundw. Appl.* **2007**, *4*, 87–90.
24. Assumpção, M.; Yamabe, T.-H.; Barbosa, J.-R.; Hamza, V.; Lopes, A.E.V.; Balancin, L.; Bianchi, M.-B. Seismic activity triggered by water wells in the Paraná basin, Brazil. *Water Resour. Res.* **2010**. [CrossRef]
25. Borchardt, M.A.; Haas, N.L.; Hunt, R.J. Vulnerability of drinking-water wells in La Crosse, Wisconsin, to enteric-virus contamination from surface water contributions. *Appl. Environ. Microbiol.* **2004**, *70*, 5937–5946. [CrossRef] [PubMed]
26. Rouhani, S.; Wackernagel, H. Multivariate geostatistical approach to space-time data analysis. *Water Resour. Res.* **1990**, *26*, 585–591. [CrossRef]
27. Deng, X.; Zhang, F.; Wang, Z.; Li, X.; Zhang, T. An extended input output table compiled for analyzing water demand and consumption at county level in China. *Sustainability* **2014**, *6*, 3301–3320. [CrossRef]
28. Fernald, A.; Tidwell, V.; Rivera, J.; Rodríguez, S.; Guldan, S.; Steele, C.; Ochoa, C.; Hurd, B.; Ortiz, M.; Boykin, K.; *et al*. Modeling sustainability of water, environment, livelihood, and culture in traditional irrigation communities and their linked watersheds. *Sustainability* **2012**, *4*, 2998–3022. [CrossRef]
29. Shi, M.; Wang, X.; Yang, H.; Wang, T. Pricing or quota? A solution to water scarcity in oasis regions in China: A Case Study in the Heihe River Basin. *Sustainability* **2014**, *6*, 7601–7620. [CrossRef]
30. Munang, R.-T.; Thiaw, I.; Rivington, M. Ecosystem management: Tomorrow's Approach to Enhancing Food Security under a Changing Climate. *Sustainability* **2011**, *3*, 937–954. [CrossRef]
31. Jones, S.; Bernhardt, K.; Kennedy, M.; Lantz, K.; Holden, T. Collecting critical data to assess the sustainability of rural infrastructure in low-income countries. *Sustainability* **2013**, *5*, 4870–4888. [CrossRef]
32. Ester, M.; Kriegel, H.-P.; Sander, J.; Xu, X. A density-based algorithm for discovering clusters in large spatial databases with noise. *KDD* **1996**, *96*, 226–231.
33. Xia, L.N.; Jing, J.W. SA-DBSCAN: A Self-Adaptive Density-Based Clustering Algorithm. *J. Grad. Sch. Chin. Acad. Sci.* **2009**, *2*, 530–538.

© 2016 by the authors; licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons by Attribution (CC-BY) license (http://creativecommons.org/licenses/by/4.0/).