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Article

Surface Water Resources Accessibility Assessment of Rural Settlement in the Yellow River Basin

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Abstract: Under the extreme shortage of water resources in the Yellow River Basin, it is of great significance to analyze the spatial distribution relationship between rural settlement and water resources for the coordinated development of human and water resources in the Yellow River Basin. However, the water allocation scheme depended on statistical data in the previous work, not on rural settlements in space. Furthermore, previous researches seldom focus on the evaluation of surface water resources accessibility according to the spatial distribution characteristics of rural settlements and water resources, especially, in the Yellow River Basin and using rural settlement as unit. Therefore, a quantitative evaluation model of surface water resources accessibility is constructed by using the GIS network analysis method, taking rural settlement as the research unit, based on three dimensions of topography, distance, and surface water resources, at the Yellow River basin scale. The results show that: (1) The surface runoff of rural settlement in the Yellow River basin is mostly less than 0.05 km/m², reaching 99.83%. In other words, the Yellow River Basin is extremely short of water resources. The surface water resources accessibility is affected by distance, topography, and surface water resources. The evaluation results show that the range of surface water resources accessibility is 0.13–0.88, with an average value of 0.47 and a standard deviation of 0.05. The High surface water resources accessibility value in the Yellow River Basin is in the east and west, and the low value is mainly distributed in the middle. (2) The range from low to high of surface water resources accessibility in 12 catchments is Sanmenxia station, Lanzhou station, Shizuishan station, Longmen station, Tongguan station, Toudaoguai station, Xiaolangdi station, Huayuankou station, Lijin station, Gaocun station, Ai Shan station and Tangnaihai station. (3) The value of surface water resources accessibility at the city scale is higher in the east of 10 cities and in the west of 1 city. However, it is lower in the west of 9 cities. And the values of the other cities are at a medium level. The correlation coefficient with primary industry GDP and surface water resources accessibility is 0.271 (N=56, Sig=0.043, in 0.05 level, the correlation is significant), which verifies the rationality of surface water resources accessibility model to some extent.

Keywords: rural settlement; surface runoff; surface water resources accessibility; the Yellow River basin

1. Introduction

Rivers are closely related to the living environment. To facilitate production and life, such as agricultural irrigation, laundry, and cooking, most of the original settlements appear along the river. However, rivers not only can block people's activities, but also can connect people's activities. Although it can provide water for human beings, it is also prone to floods devouring people's lives

and property. Water resources are rich in China, and its total amount ranks in the forefront of the world. However, its per capita possession is low and its spatial and temporal distribution is uneven in China. This imbalanced situation leads to the mismatch in spatial distribution between water resources and population. The Yellow River is the mother river of China. It feeds 12% of the population in China, among which the rural population accounts for about 75%. However, the Yellow River Basin is in an arid and semi-arid climate zone. Thus, it only accounts for 2% of the river runoff in China. Therefore, the water resources restrict strongly the existence and development of rural settlements. As an important economic region in China, the water resources in the Yellow River are an important support for the economic development of this region. However, the lack of water resources has become a key factor restricting the high-quality development of this region. Surface runoff is an important part of water resources, and plays a vital role in the production and life of rural settlements. With the continuous influence of human activities and climate change, the contradiction between the supply and demand of water resources in the Yellow River is prominent. Article 3 of the Regulations of the People's Republic of China on Water Dispatching of the Yellow River stipulates that the state implements unified dispatching of the Yellow River, following the principles of total amount control, cross-section flow control, hierarchical management, and hierarchical responsibility. In 2011, the State Council started the water allocation program in inter-provincial river basins in an all-around way, which gradually solved the problem of cut-off of the Yellow River [1]. The water allocation scheme depended on statistical data in the previous work, not on rural settlements in space. It is necessary to evaluate the accessibility of surface water resources according to the spatial distribution characteristics of rural settlements and water resources. Thus, the spatial allocation of water resources will be more reasonable in the unified allocation of regional water resources [2].

Previous studies on water resource accessibility are mostly based on the grid-scale water resource accessibility evaluation model (SHRD) or improved on this model. The indicators of these studies mainly include runoff, slope, relative height difference, and distance [3]. Li et al. added land use resistance or water intake space resistance to evaluate the water resources accessibility in Southwest China [4]. Xu et al. added a location attribute factor to the SHRD model to evaluate water prices [5]. Besides the SHRD model, Li et al. constructed a grid-scale water resources accessibility evaluation model (LRV) to evaluate water resources accessibility, based on the cumulative probability distribution of three variables, namely, length, runoff, and sight of the water network [6]. Assefa et al. evaluated the water resources accessibility based on the accessibility distance of water resources [7]. Li and Gao put forward a water resources accessibility analysis method based on network and water intake cost, considering topography, land use, and road factors [8]. Therefore, topography, water resources, and distance are the key factors affecting the accessibility of water resources. Although Zhao et al. found that the main influencing factor affecting the change of surface runoff is precipitation. The surface runoff in the SHRD model is calculated according to the precipitation and runoff coefficient of each basin [9]. However, the accuracy of choosing a runoff coefficient for a large area is fuzzy. The global land data simulation system (GLDAS) provides a long-term global distributed runoff, which is highly demanded in water cycle research and water resources management [10]. The correlation coefficient between the surface runoff provided by this data and the observed surface runoff data in the Liuxi River Basin reaches 0.81 [11]. Therefore, this data can roughly represent large-scale surface runoff.

Water resources play an important role in economic development. Usually, the lower reaches of rivers or deltas are densely populated, and economically developed areas, where water intake is convenient, with developed agriculture, water conservancy, shipping, and other comprehensive transportation. Therefore, there is a correlation between water resources and economic development. It is generally believed that the richer the water resources, the more developed the economy. Especially for agriculture, the higher the accessibility of water resources, the more developed agriculture. Farmers in the rural settlement depend on agriculture, and most of them in China are living near fields. Therefore, there is a certain correlation between the surface water resources accessibility of rural settlements and the GDP of the primary industry. Xie and Qin quantitatively

analyzed the correlation between water resources accessibility and the economy based on the SHRD model [3,12]. The experimental results show that there is a significant positive correlation between water resources accessibility and regional GDP in China. Not only in China, the development of the regional economy is constrained by water resources accessibility, but also in foreign countries, such as Bhutan [13].

This paper extracted the spatial distribution vector data of rivers and residential areas using the land use data of the Yellow River Basin in 2020. On this basis, the area and number of rural settlement patches in river buffers at different distances are counted, using the ArcGIS 10.3 spatial statistical analysis tool. Then the spatial distribution relationship between rural settlement and rivers is revealed qualitatively and quantitatively. Furthermore, combined with the surface water resources, topography, and distance, a surface water resources accessibility model (SWRA) is constructed on the GIS platform. Then, SWRA was used to quantitatively analyze the spatial distribution characteristics of rural settlement surface water resources accessibility under the whole Yellow River basin, catchment scale, and the city scale, respectively. Finally, the rationality of the SWRA model proposed in this paper was verified by the Pearson correlation analysis between city primary industry output value and SWRA at the city scale.

2. Materials and Methods

2.1. Study area

The Yellow River originates from the Bayan Har Mountains in Qinghai Province, China, and extends to Dongying City, Shandong Province. From the source of the Yellow River to the estuary, it passes through 9 provinces and 56 cities in Qinghai Province, Sichuan Province, Gansu Province, Ningxia Hui Autonomous Region, Inner Mongolia Autonomous Region, Shaanxi Province, Shanxi Province, Henan Province, and Shandong Province. The total length of the Yellow River is about 5464 km. According to the Yellow River Conservancy Commission of the Ministry of Water Resources, the total area of the Yellow River Basin is 795,000 km². As the birthplace of Chinese civilization, the Yellow River Basin has a total land area of 21,911.23 km² in urban and rural areas, industrial and mining areas, and residential areas, accounting for 2.8% of the total area of the Yellow River Basin. Rural residential areas account for about 75% of the total land area. And most residential areas are distributed along rivers.

There are many hydrological stations in the Yellow River Basin. This paper selected 12 important control hydrological stations in the mainstream of the Yellow River recorded in the Yellow River Sediment Bulletin. They are Tangnaihai station, Lanzhou Station, Shizuishan station, Toudaoguai station, Longmen station, Tongguan station, Sanmenxia station, Xiaolangdi station, Huayuankou station, Gaocun station, Ai Shan station and Lijin station from upstream to downstream (Figure 1).



Figure 1. Overview map of the study area.

Based on the method of buffer zone analysis, this paper firstly reveals the overall spatial distribution characteristics of rural settlements and rivers in the Yellow River Basin by counting two landscape pattern indices, including the number and area of rural settlements. According to the previous calculation, the area of rural settlement in the Yellow River Basin increased slowly from 1980 to 2020, with little increase in the number of rural settlement areas [14]. Therefore, this paper uses rural settlement vector data and the river network map of 2020 in the study. Then this paper takes 2km, 4km, 6km, 8km, and 10km away from the rivers as buffer zones. Furthermore, the numbers and areas of rural settlements in each buffer zone are counted respectively, as shown in Table 1.

Table 1. The proportion of rural settlement areas and numbers in different buffer zones.

Buffer distance /Km	Number of rural settlement	Proportion	Rural settlement area/Km ²	Proportion
2	21442	20.73	3388.47	21.37
2-4	13660	13.21	2481.18	15.65
4-6	11583	11.20	1966.23	12.40
6-8	9621	9.30	1606.71	10.13
8-10	8235	7.96	1251.94	7.89
> 10	38881	37.59	5164.47	32.56
Total	103422	100.00	15858.99	100.00

It can be seen from Table 1 that the proportion of rural settlement areas and numbers are 67.44% and 62.41% in the 10km away from the river. Furthermore, the proportion of rural settlement areas and numbers are 37.02% and 33.94% in the 4km buffer distance away from the river. Compared with other residential areas and numbers in the buffer zone with the same distance, the rural residential areas and numbers in the buffer zone of 2km away from the rivers account for the largest proportion. It can be seen that there is a certain correlation of the spatial distribution between rural settlements and rivers in the Yellow River Basin. Therefore, the spatial distribution relationship between rural settlement and surface water resources is further revealed by constructing the surface water resources accessibility model.

2.2. Materials

2.2.1. Data

The rural settlement data involved in this paper comes from the land use data with 30m resolution in the scientific data sharing platform of the middle and lower reaches of the Yellow River (<http://henu.geodata.cn/>, accessed on 1 May 2017) of 2020. The river network system was extracted by DEM data with a 30m resolution in 2010. The origin control upstream catchment area of each hydrological station was derived from DEM data on the ArcGIS 10.3 platform. Then it is corrected by the subbasin boundary in the Yellow River network system of the Atlas of the Yellow River Basin [15] (Figure 1).

Surface runoff data (Qs_acc) is derived from the Global Land Data Assimilation System (GLDAS) [16]. GLDAS is a global hydrological model developed and established by NASA's Goddard Space Flight Center and the National Center for Ocean and Atmospheric Prediction. Its data include surface runoff (kg/m²), snow depth (m), soil moisture (kg/m²), snow depth water equivalent(kg/m²) and so on. According to Zheng et al. and Lv et al., the surface runoff data can reflect the change in surface runoff [10,11]. Therefore, this paper directly uses this data to represent surface runoff. We extracted and processed GLDAS-2.1 data (with a spatial solution of 0.25°, equal to 25 km, and a temporary solution of 24 h) in Google Earth Engine (GEE) in 2020 [17]. Then the average value of surface runoff of 12 periods in 2020 was obtained by the grid calculator tool of ArcGIS 10.3.

The economic data selects the output value of the primary industry, which comes from the provincial statistical yearbooks in 2020. According to the National Economic Industry Classification (GB/T4754-2011) and the Regulations on the Division of Three Industries, the primary industry refers to agriculture, forestry, animal husbandry, and fishery (excluding agriculture services, forestry services, animal husbandry services, and fishery services). The gross output value of agriculture, forestry, animal husbandry, and fishery refer to the total value of all products of agriculture, forestry, animal husbandry, and fishery in monetary terms and various supporting service activities for agriculture, forestry, animal husbandry, and fishery production activities, which reflects the total scale and achievements of agriculture, forestry, animal husbandry and fishery production in a certain period [18].

2.2.2. Construction of surface water resources accessibility model

To quantitatively analyze the accessibility of rural settlements to surface water resources, this paper takes rural settlements as the research unit, and constructs the surface water resources accessibility (SWRA) model to analyze the water resources accessibility of rural settlement in the Yellow River Basin. The specific indicators include the elevation difference between rural settlements and the nearest water intake point (E) reflecting the topographic characteristic, the distance between rural settlements and the nearest water intake point (D) reflecting the distance characteristic, and the surface runoff (Qs_acc) reflecting the characteristic of surface water resources (Figure 2).

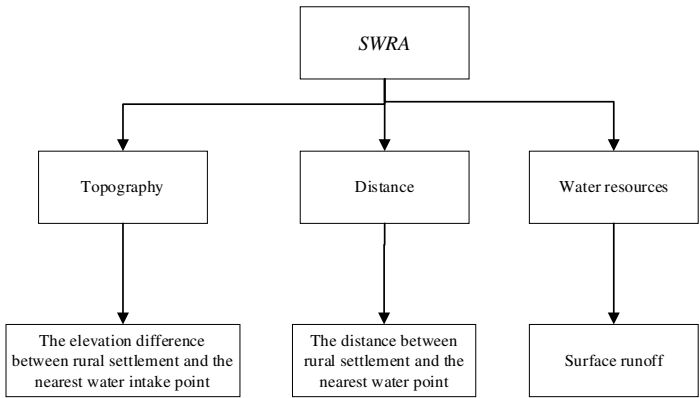


Figure 2. Index system diagram of surface water resources accessibility.

The elevation difference between rural settlement and nearest water intake point (E): The elevation difference between the rural residential area and the nearest water intake point was calculated by DEM data on ArcGIS 10.3 platform using a spatial statistical analysis tool.

The distance between rural settlement and the nearest water intake point (D): the distance between each centroid of rural settlement and the nearest water point was calculated by using the proximity analysis tool in ArcGIS 10.3 spatial analysis.

Surface runoff (Qs_acc): This paper assigns surface runoff value to the centroid of rural settlement by using the tool of "value extraction to point" in the ArcGIS 10.3 spatial analysis toolbox.

Generally speaking, the higher Qs_acc, the higher the accessibility of water resources. The lower E, the higher the accessibility of water resources. The smaller the D, the higher the accessibility of water resources. Based on the previous research achievements, the experts in water resources management achieved an agreement that Qs_acc and E had the higher impact on the accessibility of water resources in rural settlements. Then the weights of Qs_acc and E are relatively higher. Then the weight of D is relatively lower. Finally, the weights of Qs_acc, E and, D are set to 0.4, 0.4, and 0.2 respectively according to the Delphi method.

The water resources accessibility model of each rural settlement is constructed using the method of weighted summation, as shown in Formula (1).

$$SWRA = \sum (E \times W_E + D \times W_D + Qs_acc \times W_Q) \quad (1)$$

In equation (1), W_E is the weight of E , W_D is the weight of D , and W_Q is the weight of Qs_acc .

Since the dimensions of each index in Formula (1) are different, the following standardization method is adopted [19].

$$X_i^* = \frac{X_{max} - X_i}{X_{max} - X_{min}} \quad (2)$$

$$X_i^* = \frac{X_i - X_{min}}{X_{max} - X_{min}} \quad (3)$$

In formula (2) and formula (3), X_i^* is the normalized variable value, X_i is the original variable, X_{max} and X_{min} are the maximum and minimum values of X_i . For the inverse index, formula (2) is used for standardization; For positive indicators, formula (3) is used for standardization.

3. Results

The results of SWRA are examined in the whole basin, at catchment scale, and at the city scale. Because the catchments are important components of basin, the characteristics of SWRA values at catchment scale are delivered. In addition, the characteristics of SWRA values at the city scale are examined. Furthermore, in order to verify the rationality of SWRA, the correlation between SWRA and the GDP of the primary industry is explored.

3.1. The results of SWRA in the Yellow River basin

After calculation, the range of surface water runoff in the Yellow River Basin is 0-3.10 kg/m². At the same time, the surface runoff of rural settlements is extracted. The range of surface runoff value in rural settlements is 0-0.17 kg/m² (Figure 3). Based on the nearest distance, the distance between the rural settlement and the nearest water intake point is calculated. Its value range is 0.13-67038.47 m (Figure 4). Then the elevation difference between the rural settlement and the nearest water intake point is calculated, based on DEM data combined with the nearest neighbor point. The values range from -515 to 1608m (Figure 5). It can be seen from Figure 3 that the surface runoff of rural settlements is mostly lower than 0.05 kg/m², reaching 99.83% by statistics. In other words, the Yellow River Basin is extremely short of water resources. The distribution characteristics of rural settlements are along rivers, which can be seen clearly in Figure 4. There is 10.93% of rural settlements whose elevation is lower than the nearest water intake point, through attribute query statistics. There is 3.77% of rural settlements whose elevation is higher than the nearest water intake point by 500m, reaching a maximum of 1608m. The positive elevation difference greatly increases the difficulty of water intake.

The SWRAS values of each rural settlement were achieved by a weighted sum of the three standardized indicators by equation (1). The SWRA values range from 0.13 to 0.88, with an average value of 0.47 and a standard deviation of 0.05 (Figure 6). The SWRA values are divided into three levels, namely, high, middle, and low by 0.45 and 0.51, according to the spatial distribution characteristics of D , E , and Qs_acc by the Delphi method. It can be seen from Figure 6 that the SWRA in the Yellow River Basin is higher in the east and west, and is lower in the middle.

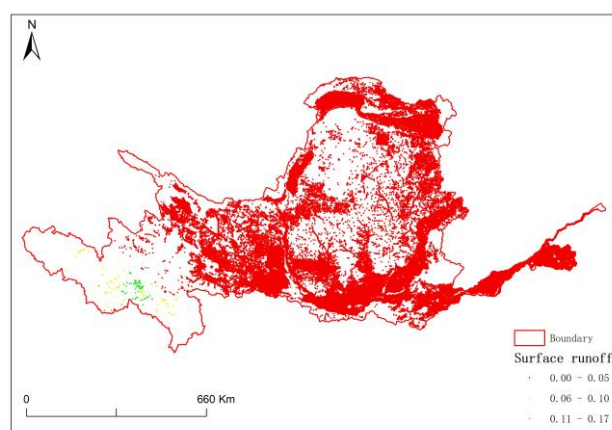


Figure 3. Surface runoff thematic map.

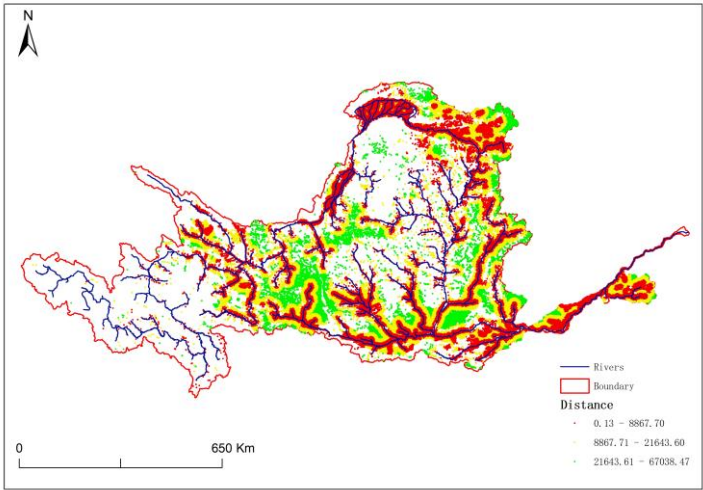


Figure 4. Distance thematic map.

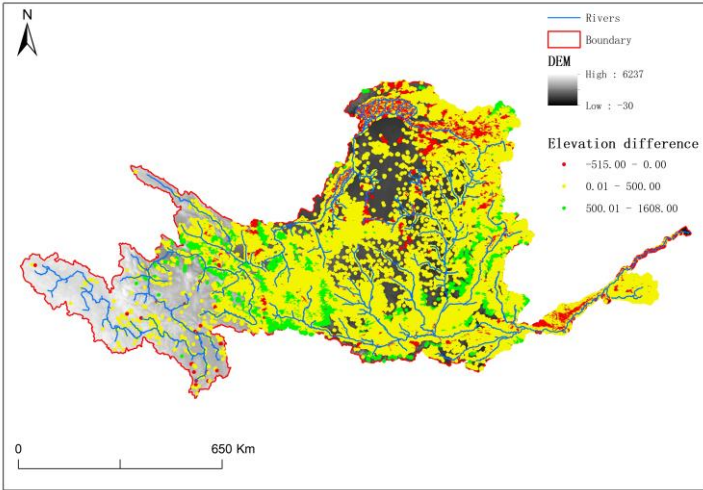


Figure 5. The elevation difference thematic map.

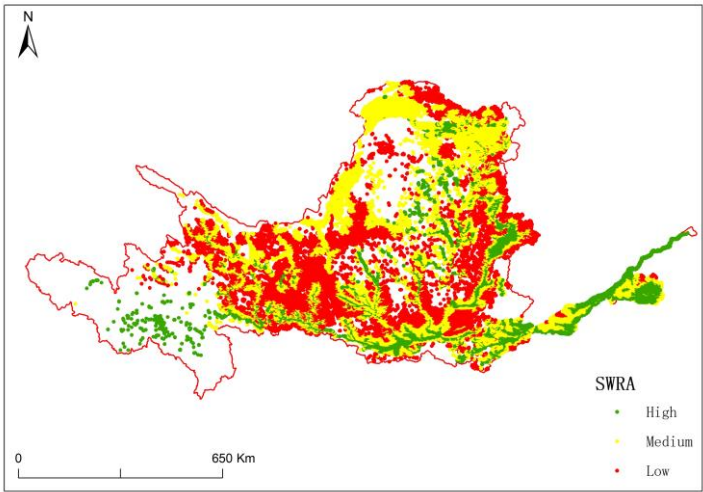


Figure 6. The surface water resources accessibility thematic map.

The distribution characteristics of SWRA values are further analyzed at the catchment scale and the city scale.

3.2. Spatial distribution characteristics of SWRA at catchment scale

The average value of SWRA in each catchment is counted based on the intersect analysis between SWRA and catchment boundaries. At the same time, the average values of the distance and elevation difference between rural settlement and the nearest water intake point are counted in Table 2. The results show that the SWRA value of the 12 catchments from low to high is Sanmenxia station, Lanzhou station, Shizuishan station, Longmen station, Tongguan station, Toudaoguai station, Xiaolangdi station, Huayuankou station, Lijin station, Gaocun station, Aishan station and Tangnaihai station. According to the classification standard of Section 3.1, the catchment SWRA value in high grade only appears in the catchments of Aishan Station and Tangnaihai Station. The SWRA values in the other catchments are at a medium level. The difference in SWRA value is minor among these catchments. Because the catchment SWRA value is the average value of all the SWRA values of these rural settlements in each catchment. It should be noted that the SWRA calculation results of this paper are only the relative level under the state of water shortage. Furthermore, the high-grade ratio of SWRA values in the Tangnaihai Station is 78.55%, while the high-grade ratio of SWRA values in the Sanmenxia Station is only 10.36%. It can be seen from Table 2 that D of the Tangnaihai Station reaches the smallest value, while D of Sanmenxia Station gains the largest value. In other words, it is relatively difficult for rural settlements in the Sanmenxia catchment to obtain water resources, while it is relatively easy for the Tangnaihai catchment, from the perspective of spatial distance. The highest value of elevation difference between rural settlement and the nearest water intake point appears in the Lanzhou catchment, with a value of 210.04 m. While, the smallest elevation difference is in the Gaocun catchment, with a value of 0.95 m.

Table 2. Statistical characteristics of rural settlement and water resources at catchment scale.

Station	D/km	Qs_acc/kg/m ²	E/m	SWRA
Tangnaihai station	6.15	0.067	96.87	0.62
Lanzhou station	7.87	0.010	210.04	0.45
Shizuishan station	10.68	0.003	114.88	0.46
Toudaoguai station	8.70	0.004	54.15	0.48
Longmen station	9.93	0.009	146.87	0.46
Tongguan station	10.78	0.013	188.06	0.47
Sanmenxia station	16.53	0.012	160.52	0.45
Xiaolangdi station	6.06	0.013	155.74	0.49
Huayuankou station	10.26	0.017	149.63	0.49
Gaosun station	9.14	0.013	0.95	0.50
Aishan station	6.74	0.020	35.61	0.52
Lijin station	7.99	0.020	80.59	0.50

3.3. Spatial distribution characteristics of SWRA at the city scale

The SWRA value of each city is equal to the mean value of all the SWRA values in the city. It is calculated by the intersection of SWRA and city boundary, firstly. Then the values are summarized by the city boundary. The result show that the SWRA values of the city range from 0.41 to 0.69, with an average value of 0.48, and a standard deviation of 0.04. The city SWRA values are divided into three levels according to the classification standard of 3.1 (Figure 7).

It can be seen from Figure 7 that the SWRA values of 9 cities are at a low level, and are distributed in the western part of the Yellow River Basin, namely Tongchuan City, Guyuan City, Baiyin City, Xining City, Hainan Tibetan Autonomous Prefecture, Yuncheng City, Dingxi City, Lanzhou City, and Haidong District. The SWRA values of 11 cities mainly distributed in the east of the study area are in high grade. They are Dongying City, Binzhou City, Dezhou City, Kaifeng City, Liaocheng City, Tai'an City, Jiaozuo City, Heze City, Puyang City and Jinan City. Besides these cities, the high-grade city distributed in the west is Guoluo Tibetan Autonomous Prefecture.

The correlation between SWRA values of city and the GDP of primary industry is revealed in SPSS 25. The results show that the correlation coefficient between cities and the GDP of primary industry is 0.271 (N=56, Sig=0.043, at 0.05 level (double tails), and the correlation is significant).

It can be seen that there is a linear positive correlation between SWRA and the GDP of the primary industry, which verifies the rationality of SWRA to some extent. However, the correlation coefficient is not high. The main reason is that the western region with abundant water resources is sparsely populated. For example, the rural settlement is less distributed in the area of the Tangnaihai catchment (e.g. Golog Tibetan Autonomous Prefecture) with a lower GDP of the primary industry, while the water resources there are abundant and with a relatively higher value of SWRA. The economic development of this region is affected by other factors such as climate, transportation, and population. In other words, SWRA is the secondary influencing factor of the economic development of this region.

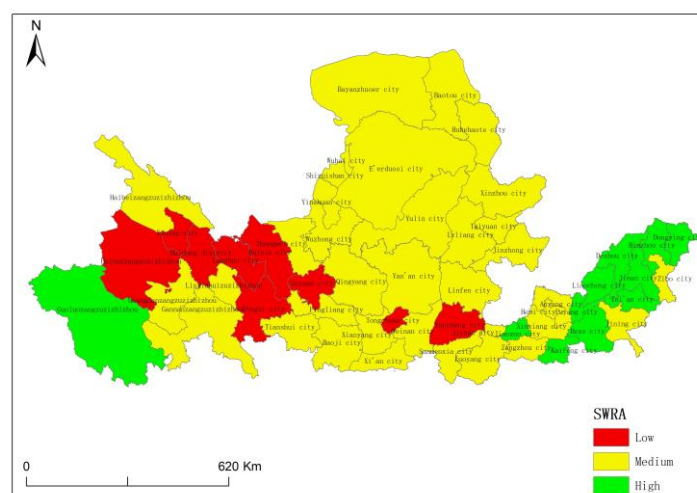


Figure 7. Surface water resources accessibility on an urban scale.

4. Discussion

With the development of infrastructure and the improvement of the tap water supply network, some rural residents gradually give up the water in natural rivers. Then rivers gradually lose their original functions [20]. Moreover, with the development of the social economy, the water quality in the rivers is gradually polluted by domestic sewage and agricultural sewage [21]. After inheritance, interweaving, replacement, connection and, other ways to promote the development of settlements, a coordinated relationship between settlements and rivers is formed [22]. And in a long-term evolution, the relationship gradually matures. Therefore, from perspective of surface water resources accessibility to analyze the accessibility of rural residential water resources, the accuracy needs to be improved. Furthermore, human factors such as the tap water network and pumping stations should be considered in the construction of SWRA.

5. Conclusions

Based on the GIS platform, the spatial distribution characteristics of rural settlements and river networks in the Yellow River Basin are studied qualitatively at first. Then a quantitative evaluation model of surface water resources accessibility is constructed by using the GIS network analysis method, taking rural settlement as the research unit, based on three dimensions of topography, distance, and surface water resources. The surface water resources accessibility of rural settlements in the Yellow River Basin is evaluated quantitatively. Finally, the rationality of SWRA is verified by the Pearson correlation analysis between surface water resources accessibility and the GDP of primary industry. The following conclusions are obtained: (1) The surface runoff of rural residential areas in the Yellow River basin is mostly less than 0.05 km/m², reaching 99.83%. In other words, the

Yellow River Basin is extremely short of water resources. The grade of surface water resources accessibility is relatively high only at the source and estuary of the Yellow River, while it is relatively low in the central region of the Yellow River Basin. (2) The average value of surface water resources accessibility at the catchment scale has minor difference. However, from the ratio of high, middle, and low grades of SWRA in each catchment area, the high-grade ratio of Sanmenxia station is only 10.36%, while the high-grade ratio of the Tangnaihai station is 78.55%. (3) The value of surface water resources accessibility at the city scale is the higher in the east of 10 cities and in the west of 1 city. However, it is lower in the west of 9 cities, and the SWRA value of the other cities is at a medium level. (4) The water resource is the key factor that restricts the development of the rural economy. There is a correlation between SWRA and the primary industry economy in the Yellow River Basin. The correlation coefficient is low, but through the test, which indirectly proves the rationality of SWRA constructed in a certain extent.

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