Construction of Green Infrastructure Based on Water Ecological Security Pattern, A case study of Songtao River Catchment in Guizhou Province, China

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Song LIU, Song Yao HUAI*, Hong Ting Pan, Tongji University, China

Abstract: China's rapid urbanization and climate change have led to increasingly severe water ecological security problems. The evaluation and construction of water ecological security pattern is an effective way to deal with water resources management, water environment protection and water disaster prevention. Green infrastructure strategy is considered as a sustainable land use planning emphasis on rainwater management. The method of water ecological security pattern shows good applicability to the construction and optimization of green infrastructure. The study area is Songtao river catchment located in southwest of China, which is faced with the problems including water resources shortage, water quality deterioration and frequent occurrence of floods. Based on GIS overlay method and Pressure-State-Response framework, the paper conducts comprehensive water ecological security pattern assessment from three current problems of water resources security, water environment security and water disaster risks. Then, green infrastructure hubs were further identified and prioritized through landscape connectivity index and river corridors were classified and optimized on the basis of the composite water ecological security pattern. Finally, the study draws several conclusions. (1) The water ecological security evaluation index system established by PSR framework provides a basis for the construction of regional green infrastructure. (2) Green infrastructure network of interconnected hubs and corridors can achieve the aims of water resource conservation and utilization, runoff pollution process control and floods resilience regulation.

Keywords: Green Infrastructure Construction; Water Ecological Security Pattern; Songtao River Catchment

1. Introduction

Rapid urbanization and climate change in China have exerted a profound impact on water ecological security. Water problems such as water resources shortage, water quality deterioration and frequent occurrence of floods indicate that it is an urgent challenge to ensure water security(Vörösmarty et al., 2010).

The evaluation and construction of water ecological security pattern provide an effective way to address the regional water security problems. Water ecological security pattern is the land use spatial pattern based on the goal of regional water security(Lin et al., 2016). The construction of water security pattern refers to the optimization of land use and spatial configuration of landscape elements that play a critical role in maintain and protect regional water security(Yu, 1996, Peng et al., 2016). Reasonable evaluation of regional water security can guarantee adequate water supply, reduce water pollution and minimize floods risks, which enhances the resilience and sustainability of regional water ecosystems(Gong, 2009).

Many studies illustrate the green infrastructure is closely related to sustainable water management(Ellis, 2013, Everett et al., 2015, Saygin and Ulusoy, 2011). Solving storm water problems and improving water cycle has become a primary goal of green infrastructure planning. Research show that green areas have reduced storm water runoff up to 100% during normal precipitation years and 77-88% during high precipitation years(Baker and Doneux, 2012). The linkage between green infrastructure and water ecological security are established due to the same aim of maintain water ecological security. But fewer literature focus on construction of green infrastructure based on ecological security pattern.

This paper aims to evaluate the water-oriented ecological security patterns to guide green infrastructure planning in Songtao River Catchment by GIS spatial analysis methods. Specifically, the main objectives of this study are to: 1) establish water ecological security index system based on PSR framework from three aspects of water resources security, water environment security and water disaster risk to construct a comprehensive water security pattern. 2) further identify, prioritize and optimize the hubs and corridors based on the composite water ecological security pattern through landscape connectivity index to build the interconnected green infrastructure network.

2. Study Area and Data Sources

2.1 Study Area

The Songtao River Catchment, with an area of 1563 square kilometers, is located in Songtao Miao Autonomous County of Tongren City in the northeast of Guizhou Province (Figure 1). It has a higher elevation on the sides of the east, the west and the north, but a lower terrain in the middle. The average elevation of the whole area is about 650 meters. The Songtao River Catchment is a typical subtropical monsoon climate where summer is hot and rainy while winter is cold and dry. The average annual temperature is 16.2 °C and average annual precipitation is 1186-1683mm, which mostly occurs from June to September. The imbalance distribution of precipitation often results in the frequent occurrence of drought and floods. People living there are mainly engaged in manganese mining, manganese product processing and agricultural planting. At present, Songtao river catchment is faced with the problems including water resources shortage such as degradation of river network structures and difficulty of water utilization, water quality deterioration due to point source pollution of manganese mines and non-point source pollution of agricultural chemical fertilizers, and water disaster risks such as frequent occurrence of floods.

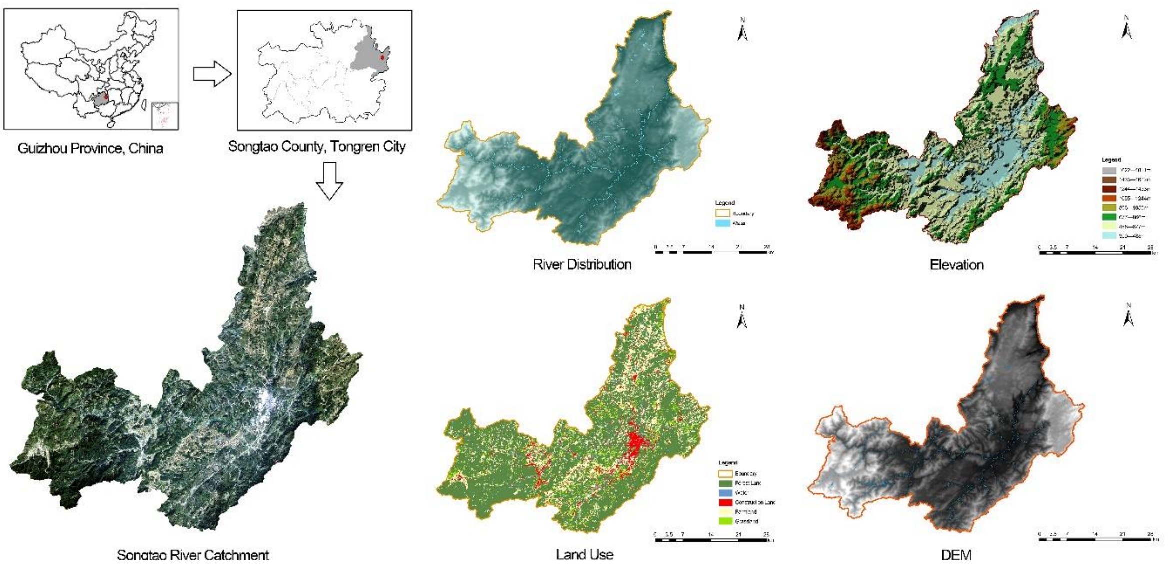

Figure 1: Location and Current Situation of Study Area

2.2 Data Sources

The data used in this study are:

(1) Elevation data was extracted from GDEM Product with a spatial resolution of 30 m from the Geospatial Data Cloud (http://www.gscloud.cn/).

(2) Land use data was interpreted through Landsat 8 images from October 8, 2013. The images were classified into five types of land use including forest land, grassland, farmland, water body and construction land.

(3) Meteorological data is obtained from the local weather station installed near the study area.

3. Methodology

3.1 General Framework

Based on GIS, the paper conducts regional water security pattern evaluation from three aspects of water resources security, water environment security and water disaster risks and puts forward the water-oriented green infrastructure construction strategies. The detailed construction steps are as follow (Figure 2)

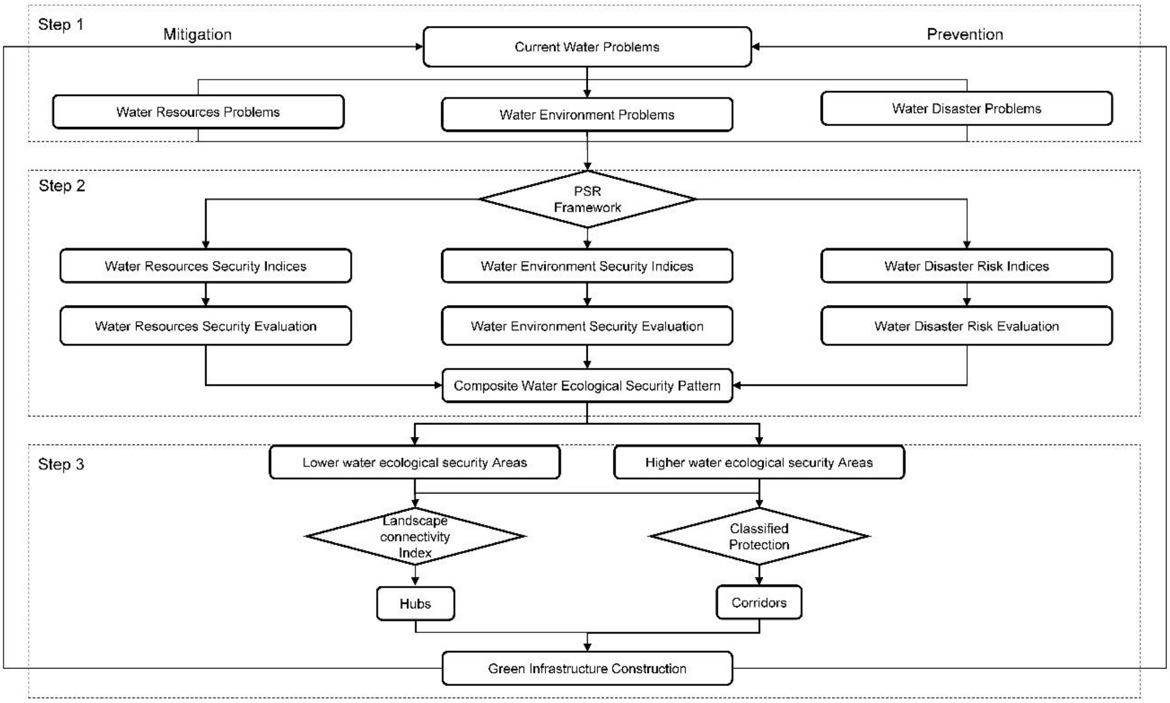

Figure 2: General Framework

3.2 Water Ecological Security Evaluation

Water ecological security evaluation is a process of mapping the water ecological problems to identify and prioritize the ecologically sensitive areas or ecologically significant areas. Areas with higher sensitivity tend to be higher significance but lower security, which are peculiarly prone to environmental problems when they are affected by intensive human activities. Through water ecological security evaluation, different levels of sensitive areas can be identified and water ecological security patterns can be constructed to provide a scientific basis for prevention and treatment of regional water security problems.

3.2.1 Water Ecological Security Indices Selection

Factors related to water ecological security are comprehensive and complex, involving natural ecosystem and socio-economic system. A systematic and logical framework is needed in water ecological security evaluation. Pressure-State-Response (PSR) framework is a conceptual framework to analyze the cause–effect relationships between society and the environment and to support decisions in response to environmental issues. It considers factors of pressures (P), states (S) and response (R), integrating the elements about natural resources and socio-economic development, which has been widely adopted in landscape assessment and environmental management(Zhang et al., 2012, Hughey et al., 2004, Wolfslehner and Vacik, 2008).

Based on the PSR framework, the paper evaluates the water ecological security in Songtao river catchment by analyzing three aspects, water resources security, water environment security and water disaster risk. According to this framework, the natural resources conditions are chosen as the state factors and the local socio-economic conditions can be regarded as pressure factors influencing the development of the catchment.

(1) Water Resources Security Indices

Water resources security refers to the state of ensuring a healthy water ecological cycle of ecosystem and maintaining sustainable living, industrial and agricultural water supply for human society. It mainly includes water source conservation, soil and water holding and water system support and allocation capability. Factors influencing these capabilities are included in the evaluation indices (Table 1).

Table 1 Water Resources Security Indices

Indices	Parameters	Extremely sensitive	Highly sensitive	Moderately sensitive	Lowly sensitive
State Indices	Distance from Rivers	0-30m	30-100m	100-200m	Above 200m
	Elevation	306-550m	550-750m	750-950m	950-1612m
	Soil Thickness	120-150cm	90-120cm	30-90cm	2-30cm
Pressure Indices	Water Facilities	6-8	4-6	2-4	0-2
	Land Use	Water Bodies	Forest Land, Grassland	Farmland	Construction Land
Value		7	5	3	1

(2) Water Environment Security Indices

Water environment security refers to the reduction of point source pollution and non-point source pollution in the river basin to ensure water quality safety. In Songtao River Catchment, the sensitivity of the area affected by point source pollution is mainly measured by the manganese mines density. However, there is no specific source of non-point source pollution, which is mainly discharged through the surface runoff into the nearby rivers randomly. Surface runoff provides quick transport mechanism for potential pollutants between the landscape and surface water bodies(Walter et al., 2000). Therefore, identifying areas that are more susceptible to producing surface runoff, that is hydrologically sensitive areas (HSA's), helps to minimize contamination into rivers and mitigate water quality risk by effective measures. Topographic index, widely applied in hydrological studies(Rousseau et al., 2004, Page et al., 2005), is chosen to identify hydrologically sensitive areas and to estimate runoff distribution to control the transport of pollutants. It is given by the following expression:

$$\lambda = \ln\left(\frac{\alpha}{\tan(\beta) K_s D}\right)$$

where α are the catchment areas, $\tan(\beta)$ is the gradient, $K_s D$ is average soil permeability rate(Woods et al., 1997).

Other factors influencing water environment security, such as precipitation, distance from rivers, land use, are also included in the evaluation indices (Table 2).

Table 2 Water Environment Security Indices

Indices	Parameters	Extremely sensitive	Highly sensitive	Moderately sensitive	Lowly sensitive
State Indices	Topographic Index	10-47	-6-10	-9-6	-17--9
	Precipitation	1550-1650mm	1450-1550mm	1350-1450mm	1250-1350mm
	Distance from Rivers	0-30m	30-100m	100-200m	Above 200m
Pressure Indices	Mine Density	70-130	35-70	15-35	0-15
	Land Use	Farmland	Construction Land	Forest Land, Grassland	Water Bodies
Value		7	5	3	1

(3) Water Disaster Risk Indices

Water disaster risk refers to the possibility of floods occurrence. It is generally understood as an interaction of hazard, exposure and vulnerability(Kaźmierczak and Cavan, 2011). The hazard can be defined as frequency and severity of damage and threats to people, property, and systems, which usually depends on geographical and meteorological factors. Areas with intense rainfall, lower terrain, dense river networks, and poor soil permeability are more susceptible to floods. The exposure is closely related to all social, economic and natural ecosystems that may be threatened by disasters. Vulnerability comprehensively reflects the extent of damage to all property present in a given area due to potential risk. The factors influencing the hazard, exposure and vulnerability are listed as follow (Table 3).

Table 3 Water Disaster Risk Indices

Indices	Parameters	Extremely sensitive	Highly sensitive	Moderately sensitive	Lowly sensitive
State Indices	Precipitation	1550-16509mm	1450-1550mm	1350-1450mm	1250-1350mm
	Flow Accumulation	7146656-15444045	3512763-7146656	1150732-3512763	0-1150732
	Topographic Index	10-47	-6-10	-9-6	-17--9
	Elevation	306-550m	550-750m	750-950m	950-1612m
	Vegetation Rate	0-0.25	0.25-0.5	0.5-0.75	0.75-1
Pressure Indices	Population Density	399-560	326-399	225-326	159-225
	Agricultural Production Value	1.15-1.65	0.95-1.15	0.57-0.95	0.55-0.57
	Water Facilities	1	2-4	4-6	6-8
Value		7	5	3	1

3.2.2 Water Ecological Security Indices Weight determination

Based on the three water ecological security indices mentioned above, the global weights of group indices and local weights of individual parameters were further determined using the Analytic Hierarchy Process (AHP) and the expert scoring method. Water ecological security index system was established as follows. (Table 4). Multiple evaluation indices can be combined through GIS overlay method to map different water ecological security levels.

Table 4 Water Ecological Security Index System

Object	Group Indices	Global Weight	Pressure-State Indices	Parameters	Global Weight
Water ecological security	Water Resources Security	0.2	State Indices	Distance from Rivers	0.0623
				Elevation	0.0240
				Soil Thickness	0.0137
			Pressure Indices	Water Facilities	0.0670
				Land Use	0.0330
	Water Environment Security	0.2	State Indices	Topographic Index	0.0556
				Precipitation	0.0122
				Distance from Rivers	0.0322
			Pressure Indices	Mine Density	0.0500
				Land Use	0.0500
	Water Disaster Prevention	0.6	State Indices	Topographic Index	0.2055
				Flow Accumulation	0.1245
				Precipitation	0.0854
				Elevation	0.0399
				Vegetation Rate	0.0249
			Pressure Indices	Population Density	0.0381
				Agricultural Production Value	0.0450
				Water Facilities	0.0367

3.3 Green Infrastructure Identification and Prioritization Based on Landscape Connectivity

Green infrastructure is a comprehensive network of interconnected hubs and corridors. The hubs are defined as ecologically significant natural areas that provide an origin or destination for ecological processes moving to or through it. Corridors are the connections that tie the system together and enable green infrastructure networks to work(Benedict and Mcmahon, 2002). Connectivity between them is a critical feature to maintain vital ecological processes and services. In addition to water ecological security evaluation, further identification and prioritization of green infrastructure space should be based on landscape connectivity.

3.3.1 Identification and Prioritization of Hubs

Probability of connectivity Index (PC) was applied in areas with lower water ecological security levels to identify and prioritize the hubs. It is defined as the probability of dispersal from one patch to another patch, which reflects the potentiality and significance of landscape connectivity. It is given by the following expression:

$$\mathrm{PC} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} a_i a_j p_{ij}}{A_L^2}$$

where $a_i$and a_j are the areas of the patches i and j, and A_L^2 is the total landscape area. p_{ij} is defined as the maximum product probability of all possible paths between patches i and j(Saura and Pascual-Hortal, 2007). The higher PC value indicates the better landscape connectivity and more dominant role in hubs. Probability of connectivity Index (PC) was calculated and classified through Conefor Sensinode 2.2 among the areas with lower water ecological security levels.

4. Results

4.1 Water Ecological Security Pattern

4.1.1 Individual Water Ecological Security Pattern

(1) Water Resources Security Pattern

Fig. 3 shows the security levels and evaluation values for the water resources security of the Songtao catchment, ranging from higher security to lower security (0.2-1.32). The higher value indicates the higher sensitivity and the lower security of water resources. Areas with lowest water resources security are mainly located close to reservoirs, the river sources and dense river network in the north and in the middle of Songtao River Catchment, which covers 2.40% of total area with 37.47km^2 . In the future planning, it is necessary to enhance the protection of water source and build suitable buffer zone to ensure the safety of water resources. In addition, water facilities such as reservoirs should be improved or enlarged to satisfy the needs of rainwater sustainable utilization.

(2) Water Environment Security Pattern

Fig. 3 shows the security levels and evaluation values for the water environment security of the Songtao catchment, ranging from higher security to lower security (0.2-1.35). Regions of high mines density tend to suffer from point source pollution while farmland and construction land are of highly risk to non-point source pollution. Hydrologically sensitive areas with lower terrain are prone to generating and transporting runoff pollution to water bodies. These areas are in lowest water environment security levels, which are mainly distributed in the southeast of Songtao River, accounting for 5.78% of total area with 903.41km^2 . High security level and medium security level lie in forest land and grassland, which occupy the most area of the catchment. In the future planning, it is essential to control the impact of human activities on the water source and maximize the role of green space in contaminants interception and reduction.

(3) Water Disaster Risk Pattern

Fig. 3 shows the security levels and evaluation values for the water disaster risk of the Songtao catchment, ranging from higher security to lower security (0.68-3.86). Areas with higher construction intensity, lower terrain and lower vegetation coverage in the basin have higher flood risk, most of which are concentrated in the river valleys. It covers 3.45% of total catchment area with 53.92km^2 . Most of sensitive and low-sensitive areas are mainly located in forest land and grassland.

4.1.2 Composite Water Ecological Security Pattern

Through GIS overlay of three patterns by individual weight, composite water ecological security pattern can be constructed (Figure 3). Areas with lower water ecological security level are mainly distributed close to the main stream of Songtao River, which are the top priority areas for protection.

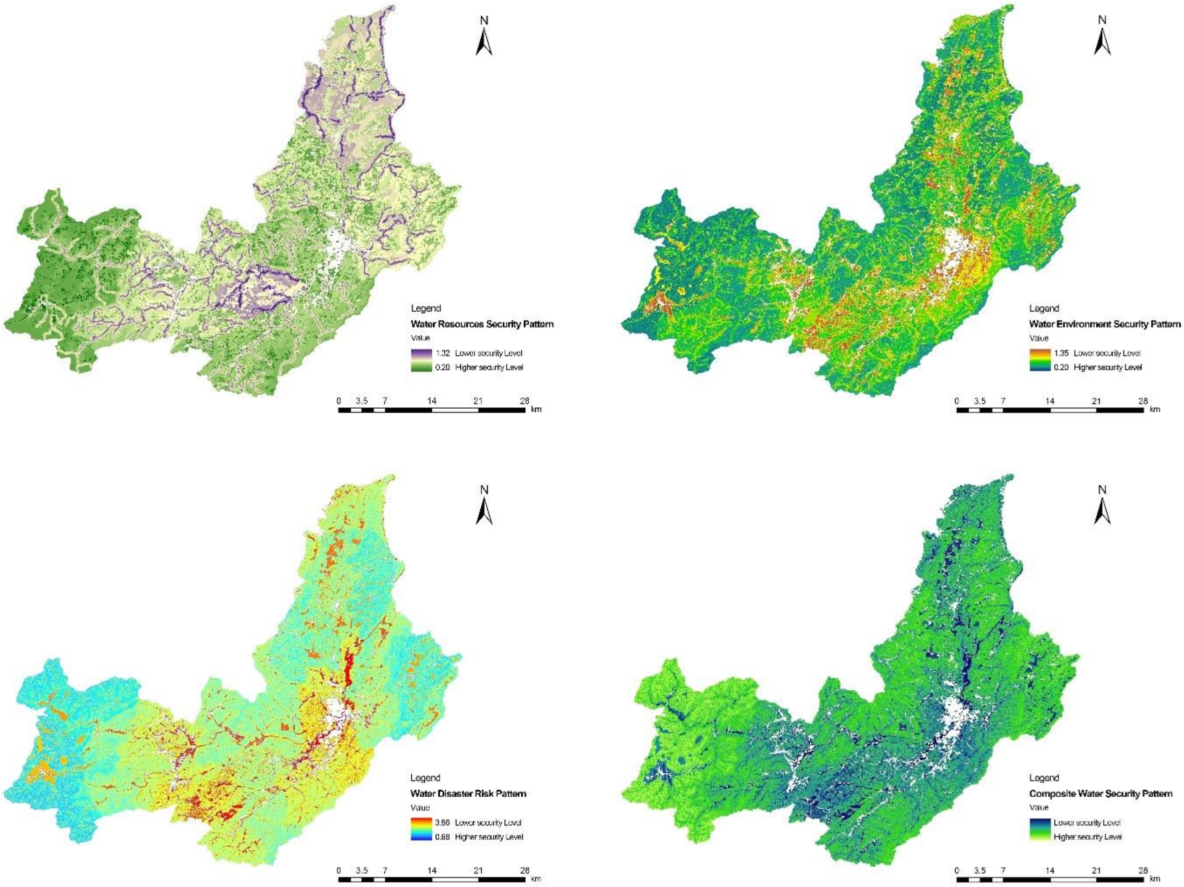

Figure 3: Individual and Composite Water Ecological Security Pattern Results

4.2 *Green Infrastructure Construction*
4.2.1 Hubs

Probability of connectivity Index (PC) was calculated and classified through Conefor Sensinode 2.2 into three categories: PC<0.04、 0.04≤PC≤0.4、PC>0.4, which represent the extremely important hubs with best connectivity, important hubs with good connectivity and slightly important hubs with moderate connectivity. All three categories were included in the green infrastructure hubs (Figure 4).

4.2.2 River Corridors

Based on the composite water ecological security pattern, the river corridors are classified into three levels of protection and optimization (Figure 4). The first level of rivers refers to the main stream of Songtao river system with the purpose of decreasing the floods risk. It is necessary to add additional wetlands, reservoirs and detention ponds to link with main stream to build blue and green flood passages. The second level of rivers are the branches of main stream in the whole catchment, whose function is to prevent contaminants from discharging into the rivers. Some buffer zones of different width can be delimited according to local ecological situation. The third level of rivers are the potential runoffs determined by topographic and soil data, which can collect the storm water and connect with the branches to facilitate the storage and usage of water resources.

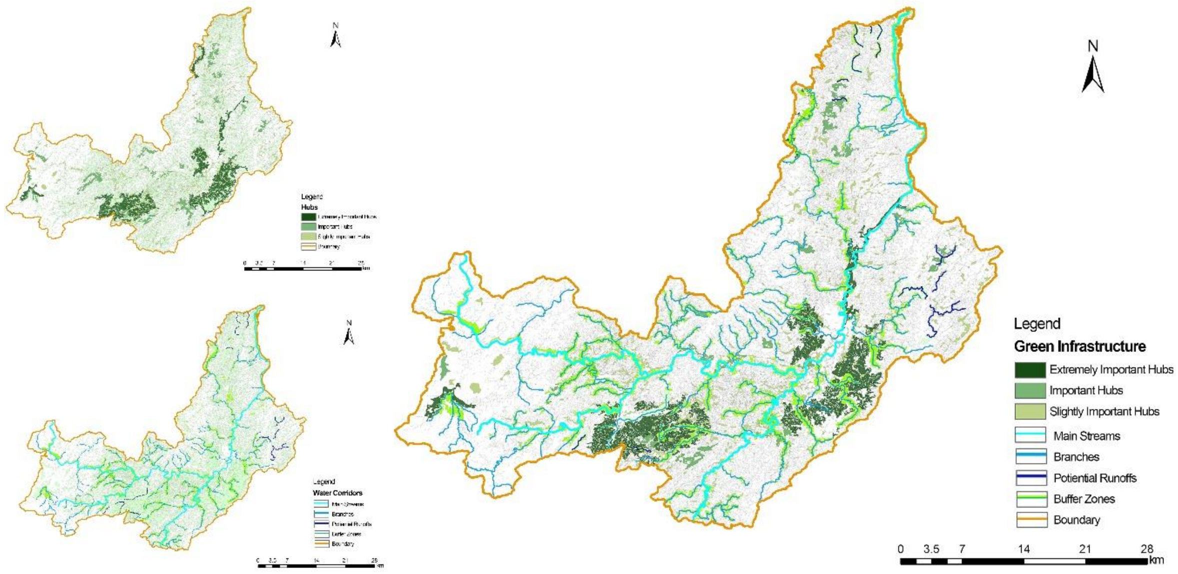

Figure 4: Green Infrastructure Construction Results

5. Discussion

5.1 Methodological Advantages

Based on the understanding of current water security problems, the research expanded the traditional concept of water security pattern by analyzing the cause–effect relationships between human society and environment and including the socio-economic dimension into PSR indices system. In addition, considering the process of water ecological cycle and the typical attributes of green infrastructure, the research made further identification and prioritization of hubs according to the probability of connectivity index to produce a more precise outcome.

5.2 Limitations and future research direction

In the process of indices weight determination, although expert scoring method is feasible, it couldn't fully reflect the influence degree of each index on water security problems. The evaluation results need to be continuously improved in accuracy. As green infrastructure is a multifunctional land use planning method, future studies may involve multi-objective orientated evaluation process.

6. Conclusion

Taking Songtao River Catchment as a study area, this study identified the water ecological security patterns based on the PSR framework from three aspects of water resources security, water environment security and water disaster risk. Then, on the basis of the composite pattern, we applied the further prioritization of green infrastructure space through landscape connectivity index. The hubs were graded into three categories of extremely important, important and slightly important. The river corridors were also classified into three categories of main streams, branches and potential runoffs. The interconnected green infrastructure was constructed combining the hubs and corridors. The construction of green infrastructure is conducive to healthy water cycle and can facilitate adequate water resources supply, water pollution reduction and floods risks resilient regulation.

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