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Assessment of Huixian Karst Wetland for Local Water Augmentation in Guilin, China

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Abstract: Due to the rapid exploitation of water resources in the Huixian karst wetland in the southwest of China in the past decades, the wetland has suffered from shrinkage in size and serious degradation of ecological functioning. To assess how much water within the wetland could still be taken out for local supply purposes while the wetland can still be kept in its normal ecological functioning. Through the use of multi-methods, including field surveys by a multi-disciplinary team, water balance, Remote Sensing, GIS and numerical simulation, this paper characterizes the wetland regime of the study area and finally determines scenarios of water resource utilization for local water supply within acceptable parameters of wetland ecological health. Through the analysis of the methods, it was found that the hydrological characteristics of the study area were conditioned by not only the karst water but also the regional precipitation fluctuations. A zone of mobile watersheds for Lake Mudong was established as opposed to a conventional single watershed. If the wetland ecosystem is kept at the current status of class III, a scenario of withdrawal of up to 20% of lake inflows could be accommodated. The results and their approaches would provide much-needed information for the protection of the wetland and its sustainable water utilization per se. It would offer a basic reference for similar problems in karst areas of southwest China and other areas alike.

Keywords: Huixian karst wetland; RS; GIS; hydrological characteristics; water budget; numerical simulation

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1. Introduction

Wetlands are among the most productive ecosystems worldwide and have very important roles in aspects of hydrology, ecological function, and so on [1–3]. As human activity, such as agricultural development and rapid urbanization, increases, wetlands get dwindled significantly each year and go through functional degradation on a global scale for a long time [4–9]. Especially karst wetlands with hydrological characteristics conditioned by karst terrains provide the key habitats for plants and animal species for local regional biodiversity [10–13]. Due to the characteristics of karst terrains, karst wetlands are also sensitive to climate change and global change [14–17]. The southwest of China, which lies in the center of East Asia and is one of the world's three contiguous karst development regions, is a typical region with a fragile ecological environment [18–21]. The karst wetlands have appeared to be undergoing serious degradation in the region [22]. Huixian karst wetland, located in the southwest of China, is the largest wetland within the altitude area of middle and low latitude in China and is also a representative of the subtropical karst landscape in the world [23,24]. As being popularly called the Kidney of Guilin, it plays a vital role in local ecological functions and water resource regulation [25,26]. Due to anthropogenic disturbances, the wetland has undergone serious modification. The wetland flow regime was once modified for navigation purposes during the Tang Dynasty; hence, the wetland was a constructed one, and it could deteriorate even further if the health of the Huixian wetland was not assessed while being utilized. The wetland suffered from being shrunk in size, resulting in serious degradation of ecological functioning. During the period from the 1970s to the present, the size of Huixian wetland was reduced from 120 km^2 to 24 km^2, and the surface area of the perennial water body became less than 6 km^2 [27]. Shrunk wetland worsens the ecological environment and has a serious influence on local tourism.

Until now, there have been some studies relevant to Huixian karst wetland. Cai et al. (2009) [28] revealed the changing environment of the Huixian wetlands at a regional scale in the past 40 years by remote sensing (RS); Zhu et al. (2020) [29] discussed that the water level of the core of Huixian wetland was related to the process of hydrological dynamics; Zou et al. (2019) [30] suggested how to protect and rehabilitate Huixian wetland by considering karst formulation, evolution trend, and hydrogeology. The pressure-state-response model (PSR) was also used for assessing the health status of the Huixian wetland [31]. The above-mentioned pieces of literature are mainly focused on the evolution mechanism, ecological values, and restoration advice for Huixian Karst wetland at the regional scale. Although the previous work lays the foundation for further resource-oriented investigation of the Huixian Karst wetland at a local scale, a realistic hydrogeological conceptual understanding of the wetland is still yet to be firmly established. For instance, the unique mechanism of mobile groundwater watersheds revealed during the investigation is poorly understood.

Due to the lack of historical monitoring data on hydrology in the study area, the quantification of karst water resources could not be readily carried out, and a feasibility study of the sustainable utilization of the wetland water have not yet been investigated. For a realistic local water supply strategy, the wetland needs to be assessed. This paper results from the work that determined the availability of wetland water for local sustainable development through multiple methods, including water balance, remote sensing (RS), GIS, and numerical simulation.

2. Site Description

As seen in Figure 1, Huixian Karst Wetland is located in Huixian Town, Lingui County, southwest of Guilin City, about 30 km away from the Guilin urban area. The wetland is mainly distributed in Mudong Village, Siyi Village, Xinmin Village, Mamian Single Tail Village, Wenquan Village, and Sitang County's Dawan Village under the jurisdiction of Huixian Town of Lingui County, and Zhuyuan Village under the jurisdiction of Yanshan District, involving 47 natural villages of about 22,000 people in 3 townships (towns) of two counties (districts).

In terms of climate, Huixian wetland belongs to a typical subtropical monsoon climate. The annual mean precipitation is approximately 2000 mm, with abundant rainfall. However, the precipitation mostly occurs from March to August, of which the distribution over time and space is extremely uneven [32]. In terms of hydrogeological conditions, Huixian wetland lies in a region of extensive karstification with strong hydraulic connections between surface and groundwater.

Under the influence of geologic structure, Huixian wetland lies on a Mudong tectonic basin with a central low-lying depression within the north and south primary watersheds. The terrain is relatively flat with a slight depression in the core area of the wetland, which consists of lower Carboniferous carbonate rocks, located in the red soil zone, underlain by a layer of weathered clayish residues of limestone with a thickness of up to 1–4 m, providing good water storage conditions. In addition, the weathered clay found at the bottom of the lake acts as a layer of an aquitard, preventing wetland water from leaking downward vertically. Upper Devonian Rong County Formation (D3r) with well-developed karst is mainly distributed on the east and west sides of the core area. Lower Carboniferous Yanguanian Stage sandwiched between Upper Devonian Rong County Formation (D3r) and Datangian Stage (C1d) layers, and Datangian Stage (C1d) layer, with weak karst development, are distributed in the core area of the wetland (Figure 2).

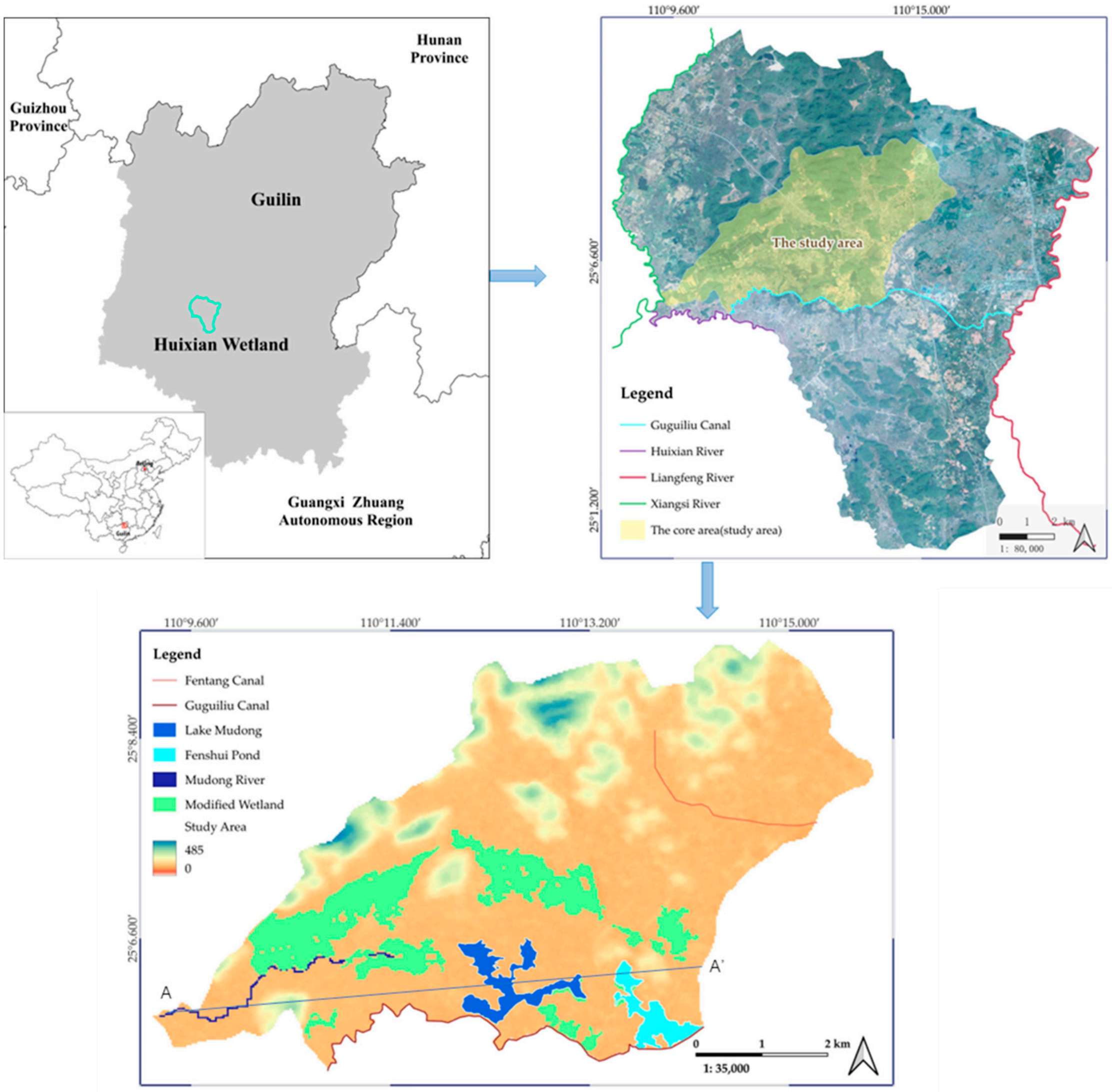

Figure 1. The geographical location of Huixian karst wetland is 30 km from the Guilin urban area, southwest of China.

Most of the water drains from the north and south of the karst terrain, converging towards the core area of the wetland catchment, where a perennial lake forms with swamp wetland. The core part of the natural wetland was partially constructed during a period of the Tang Dynasty to channel karst water flow from the dammed Fenshui pond and drain it duly via the Guguiiliu Canal (i.e., the east and west canals) to the Gui River and Liu River, respectively. As part of the core wetland, Fenshui pond and Guguiliu Canal form the salient water bodies within the wetland (Figure 1), which is defined as the study area (referred to as the area) in this paper.

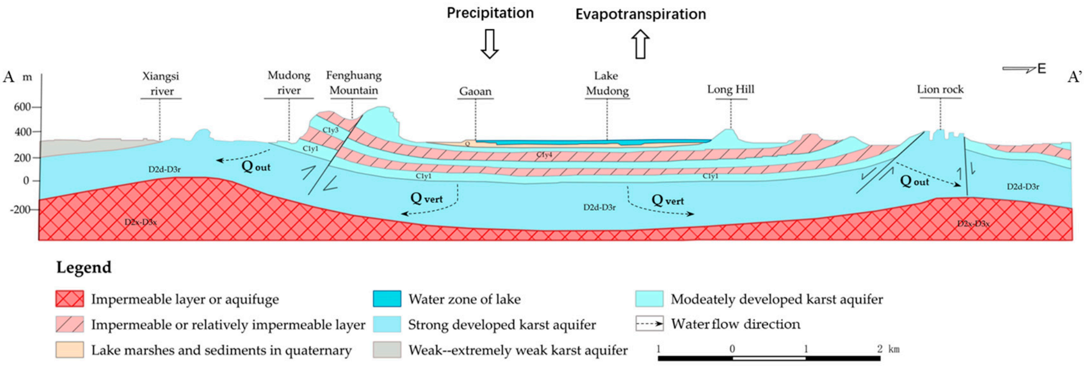

Figure 2. Sketch of west—east crosssection (**A**,**A′**) of the hydrogeology of the Mudong basin in the core area of the wetland (after D. Cai et al. 2012 [23]).

In the area, the Mudong River, which runs through Lake Mudong, is the main drainage in the west of the area. Guguiliu Canal is the southern boundary of the area. Lake Mudong is the central discharge area of Huixian wetland, the largest lake wetland, in which hydrological fluctuations are conditioned by local geology, geomorphology, and hydro-ecological characteristics. It is found that the constructed wetland is also located in the secondary watershed area between the Li River basin and the Liu River basin. The Guguiliu Canal, which runs through the wetland, connects the two basins. Hence, the water within the wetland is a shared resource for both the Liangfeng River catchment within the Li River basin and the Xiangsi River catchment within the Liu River basin.

Water in Lake Mudong outflows eastwardly along the east branch of the Guguiliu Canal into the Liangfeng River and westwardly along the Mudong River into the Xiangsi River, respectively. This study focused on wetland water utilization. The work presented in this paper adopted multi-approaches to a macro-assessment of water resource utilization in the watershed area. The scientific question for this study was: what amount of total utilizable water can be utilized for local growth and development without the current wetland health status being degraded?

3. Methodology

Several methods were reviewed for this study. Appropriate methods that were considered feasible for investigation with specific purposes were selected and used. The selection of methods took into consideration the purpose of the investigation and the availability of the data required. Based on field investigations, the following aspects can be discussed: The water balance as the basis of this study was used to determine the integrity of the catchment of the study area. Analysis of remote sensing (RS) data and spatial analysis of the Geographic Information System (GIS) are adopted not only to solve the problem of a lack of historically observed data but also to deduce the main causes of degradation and hydrological regimes in the study area. With the conceptual model firming up, the numerical simulation could finally be used to verify the hypothesis of the water augmentation locally. Multi-methods were adopted and integrated in such a way that the current condition of the wetland is assessed, the reference condition is deduced, and the modification of the wetland water resources is evaluated, with the aim of enhancing its potential water utilization while maintaining the ecosystem within an acceptable margin of modification.

3.1. Field Investigation

Field surveys were conducted from 2017 to 2022 for the authors to gather monitoring data for the karst water regime. In the process of the investigation, 13 surface water monitoring stations and 9 wells for groundwater were established with data obtained from the monitoring network, which became available in 2018 (Figure 3).

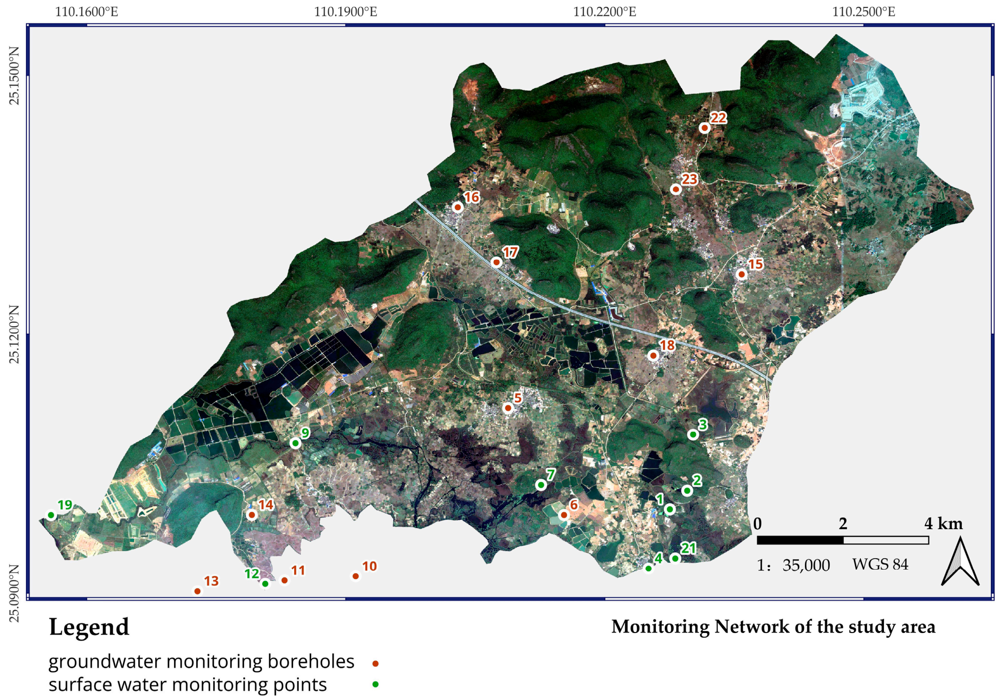

Figure 3. Distribution of the observation sets available on the monitoring network in the area.

Among the identified stations, borehole numbers 5#, 6#, 8#, 10#, 11#, 13#, 14#, 15#, 16#, 17#, 18#, 22#, and 23# were the locations of groundwater monitoring, while 1#, 2#, 3#, 4#, 7#, 9#, 12#, 19#, and 21# were for surface water, as shown in Figure 3. Most of the surface water stations are within the wetland except 19#, which is located at the confluence of the Mudong River and the Xiangsi River in the far west. Based on the analysis of the surface water monitoring data, the water level in the area responded fast to intensive precipitation and fluctuated with rainfall almost instantly, having a great correlation with rainfall. The change in surface water level was affected directly by atmospheric precipitation (Figure 4).

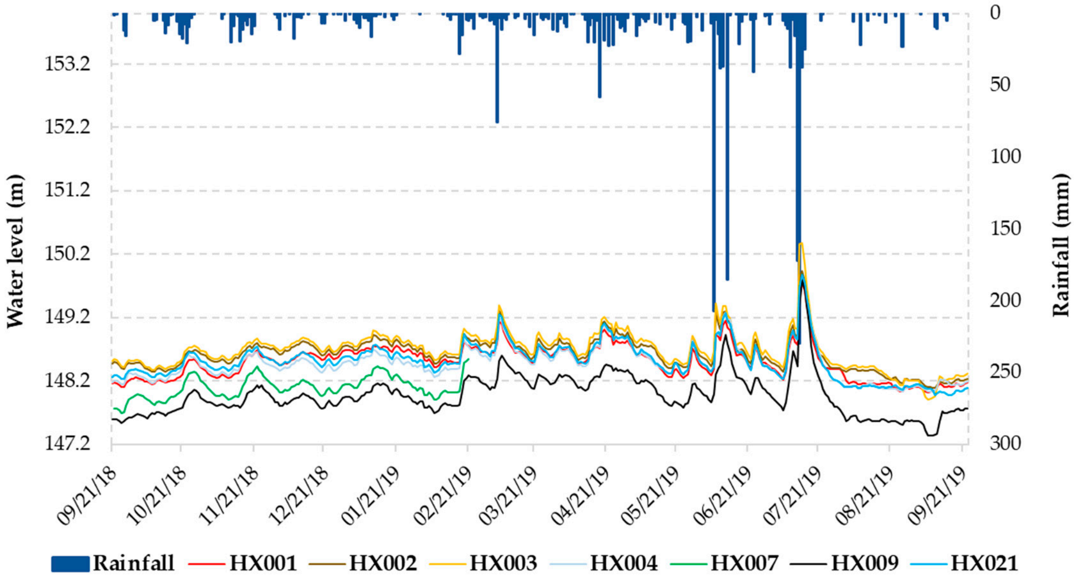

Figure 4. Showing the corresponding relationship between surface water level and precipitation through surface water monitoring data.

Surface water flow in the area showed a perfect corresponding relationship with rainfall events. Arrivals of peak water levels were often delayed by 1–3 days, depending upon rainfall intensities (Figure 5). It was found that if the cumulative rainfall exceeded 90 mm per day, the arrival time of a peak level would be within the same day, which implies that the rapid flow was most likely facilitated by the karst pipe flow upstream.

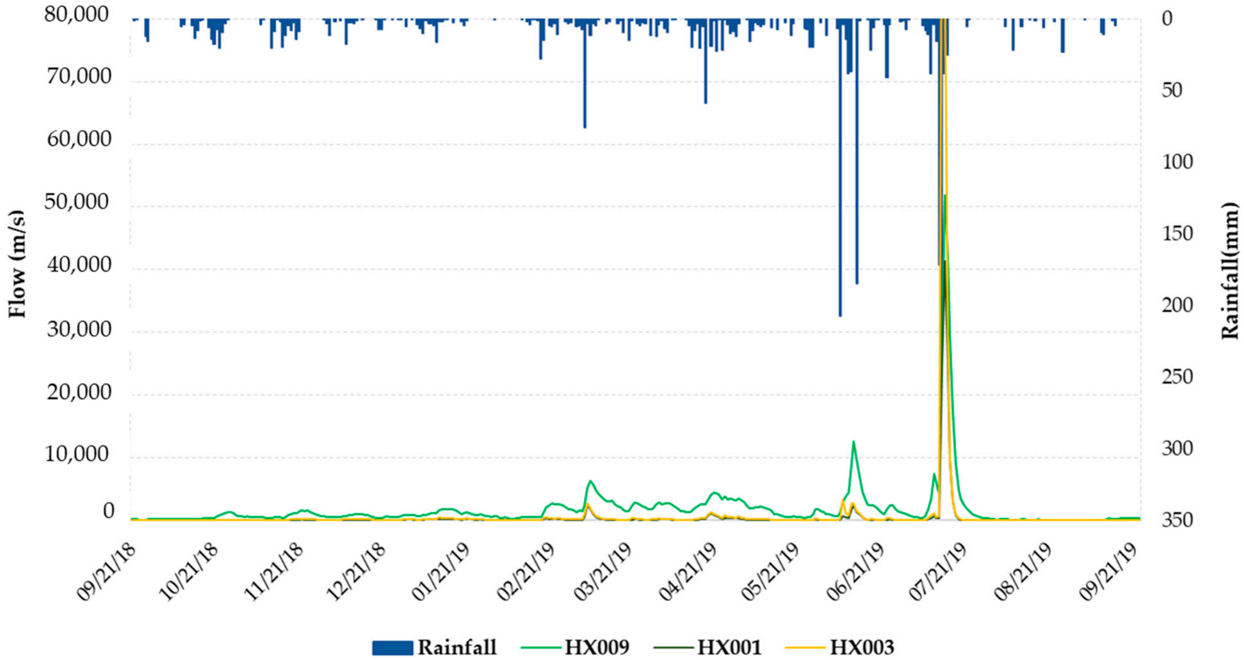

Figure 5. The corresponding relationship between surface water flow and rainfall.

The analysis of data from groundwater monitoring boreholes showed that the dynamic variety of the groundwater tables are consistent with the rainfall fluctuations, as expected. During this period, the groundwater system continued to play a critical role in water storage and flow regulation (Figure 6). Based on the analysis, it was observed that the augmented supply of water resources within the area could come from karst water generated by local precipitations.

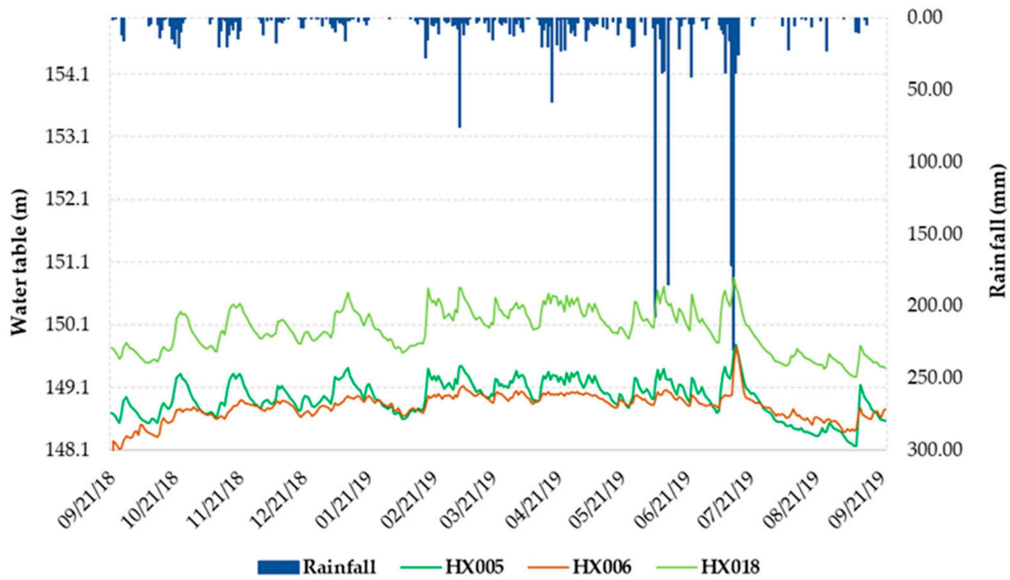

Figure 6. The corresponding relationship between the groundwater table and the rainfall.

3.2. Water Balance

A water balance method is commonly used to understand the components that constitute a catchment system [33–36]. This approach was used for the verification of each component, which was identified based on the field investigation within the whole study area, to predefine the water circulation paths, which could pave the way for the following analyses. The area belongs to a fairly enclosed ecohydrological system. However, this region is located in a watershed area, and it is especially required to determine water circulation routes at a regional scale using a water balance checkup (Figure 2). According to the hydrogeological conditions, Lake Mudong, Fenshui Pond, and Guguiliu Canal, which are referred to as the Lake Mudong drainage zone, were the focal points of the area. Therefore, the water balance analysis was taken for the drainage zone at a macro scale, and each of the water balance components within the zone was independently determined to assess if they could be balanced out within the zone. The balance was used to confirm whether the stored water would leak vertically or not, namely whether or not precipitation minus evapotranspiration equals water flux (karst water runoff) within the scope of the area.

For the karst water of the area, there were three subcomponents: the first one drains the surface water in the Fentang Canal of Mamian village and flows out of the area in the far northeast; the second flows into the dammed Fenshui Pond via karst pipes originating from the north area and is discharged out of the area via the east channel; and the third discharges the water from Lake Mudong via the Mudong River toward the west (Figure 7). The three subcomponents described above constitute the total karst water runoff in the balance calculation.

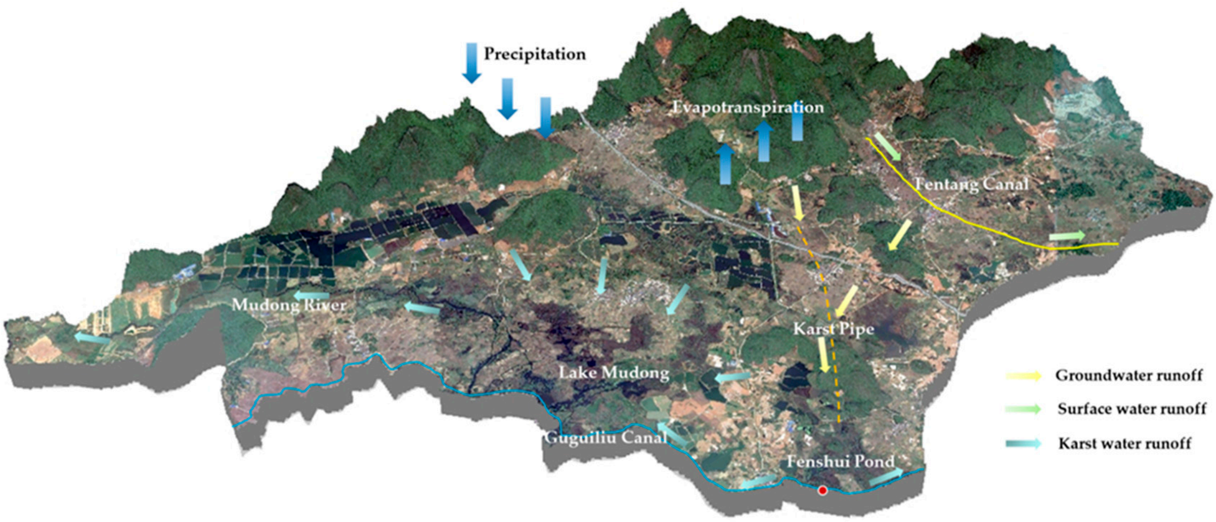

Figure 7. A sketch of flow routes is shown for the water balance of the Lake Mudong zone.

For the study area, the total incoming water equals the outgoing at a steady state, which is used to check the integrity of the target area involved and can be expressed as follows: $P = E + R$. Where P is precipitation and inflow that represent the total incoming water of the area; E stands for evapotranspiration (the sum of the evaporation from the surface and plants); R refers to the total outgoing water of the area, which consists of three parts: R_1, the first one drains the surface water in Fentang Canal of Mamian village and flows out of the area in far northeast; R_2 discharged out of the area via the east channel; and R_3 discharges the water from Mudong lake via Mudong River toward the west. Therefore, $P = E + R_1 + R_2 + R_3$.

1. Precipitation and inflow

Due to the limited duration of the constructed monitoring network in the area, the automatic recorders of hydrological monitoring were just equipped to obtain the data in situ starting in 2018, which were downloaded and used for the precipitation and inflow (karst runoff) estimation required for the flow route verification purpose. However, there is no complete set of the evapotranspiration data, which were deduced by using the remotely sensed data over the area.

2. Evapotranspiration

Evapotranspiration, including from both lands and water bodies, is an indispensable part of the analysis for regional water circulation checkups, which is a key part of the balance of land energy and water [37]. The energy balance model was usually adapted to retrieve evapotranspiration [38,39]. In the water balance verification checkup of the area, evapotranspiration was deduced from an energy balance model through Landsat satellite images, and finally, the average evapotranspiration was estimated at 623.64 mm per year, which is equivalent to the water volume of 25.51 million m^3, as seen in Figures 8 and 9.

3. Runoff

Following the information obtained from the in-situ monitoring stations, the annual precipitation was estimated at 2245.8 mm in the year 2018, which is equal to the water volume of 91.85 million m^3. The data for the three paths of karst water runoff are from three points (R_1, R_2, R_3) as indicated in Figure 3.

As can be seen in Figures 3 and 7, for R_1 Fentang Canal was 599.5 L/s and the annual outflow was 18.9 million m^3; for R_2, flow discharge from the east branch of Guguiliu Canal was 315.90 L/s and the annual outflow was 9.96 million m^3; for R_3, the amount of water in Mudong River flowing down into Xiangsi River was measured at 1028.54 L/s and the annual outflow was estimated at 32.44 million m^3.

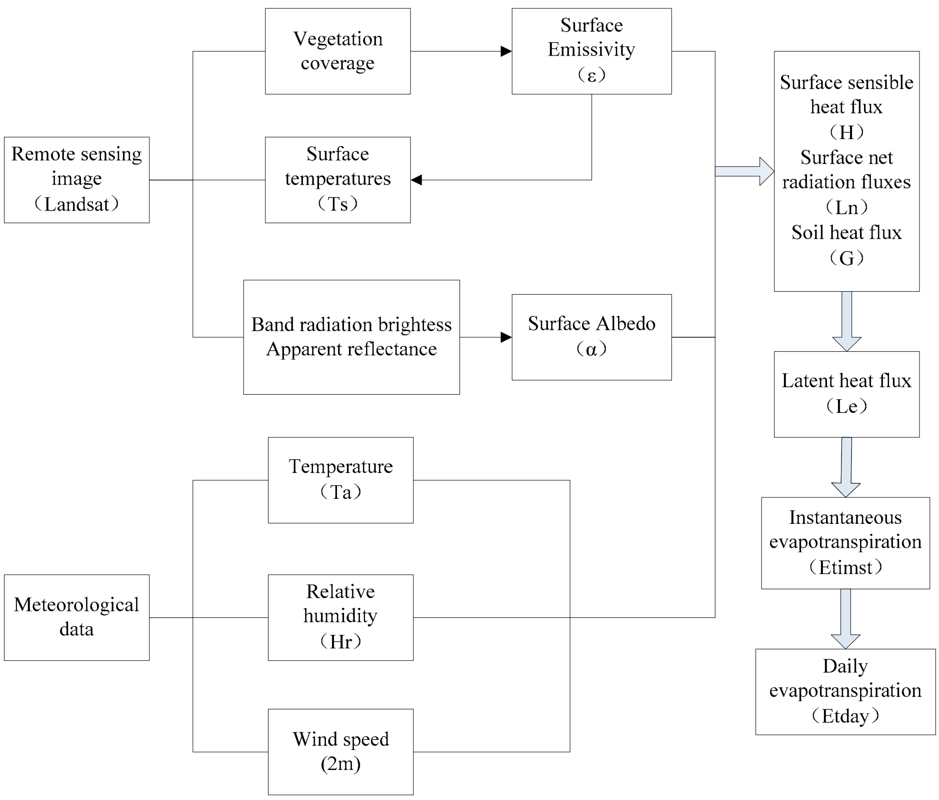

Figure 8. Flowchart of evapotranspiration inversion in the energy balance model.

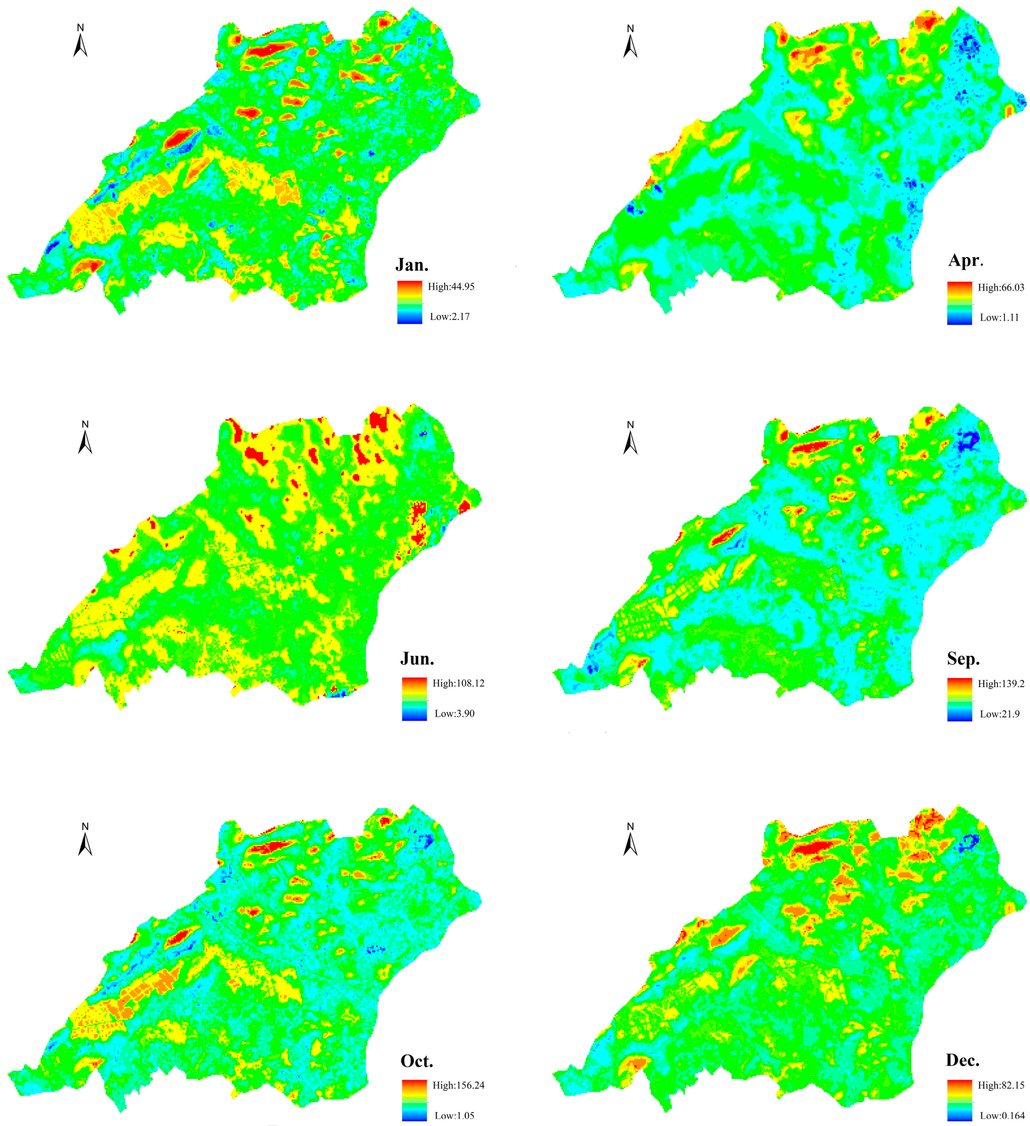

Figure 9. The result of evapotranspiration inversion over the area.

3.3. Remote Sensing

Understanding the evolution of the area and analyzing the dynamic variety of water regimes on a large scale for a long time was considered important. In the absence of monitoring data, the interpretation of remotely sensed data becomes an essential way to obtain effective information. Remote sensing (RS) is a widely used complementary tool for water resources assessment, which could be efficiently used to obtain reliable hydrological data and information on temporal and spatial scales [40–43], which could provide great support for an area lacking monitoring data and were used to deduce information on the long-term characteristics of the wetland. A further explanation for hydrologic characteristics was established, which forms the scientific basis required for sustainable utilization of the water resource in question.

Landsat satellite images for a period from 1987 to 2017 and DEM with a 30 m resolution of GDEMDEM were collected and collated as the source data for the study in this paper. The satellite images were selected for the normal period from September to December, during which cloud cover after checking was less than 10%. Then, there were 27 images in total chosen for the analysis, including 22 Landsat TM images, 5 Landsat OLI images, and 1988, 1990, 1997, and 2012, where no suitable images were found, as shown in Table 1.

Table 1. Selected satellite remote sensing images were used in the Huixian wetland.

Satellite	Sensor	Resolution/m	The Time
Landsat	TM	30	October 1987, October 1987, October 1989, October 1991, October 1992, October 1993, October 1994, October 1995, October 1996, October 1998, September 1999, December 2000, November 2001, October 2002, November 2003, September 2004, October 2005, November 2006, January 2007, November 2008, October 2009, August 2010, November 2011
Landsat	OLI	30/15	October 2013, September 2013, December 2013, January 2014, August 2014, December 2014, January 2015, July 2015, October 2015, February 2016, July 2016, December 2016, January 2017, April 2017, October 2017, September 2018

According to the joint surveys with the Institute of Karst Geology of CAGS (Chinese Academy of Geological Sciences), the boundary of the area was demarcated, with an area of 40.9 km^2 in size determined. It was observed that there was good vegetation coverage of more than 90%, eutrophication, and swathes of water hyacinth in rivers and lakes. The presence of the shadows of the mountains and the water hyacinth presented challenges to extracting true information about the water surface area. In this small geographic scale, the water hyacinth was far away from the thalweg, not located within an area of thalweg influence. The presence of water hyacinth would cause an overestimation of vegetation distribution; hence, this was rectified by using the humidity index.

Firstly, radiometric calibration, atmospheric correction, and orthographic correction were duly carried out for Landsat 5 TM and Landsat 8 OLI images. Due to the lack of data, the slopes were calculated using ENVI and DEM with the aid of visual interpretation to remove the disturbance of the shadows of the mountains. The visual interpretation combined with ground truthing could solve the problem with reasonable confidence. Secondly, the humidity index was chosen to analyze and extract the water surface area of the wetland in question to reduce the influence of water hyacinth. The humidity of the water surface covered by water hyacinth was also higher than that of the water without hyacinth present. At the same time, the part of the bands in the Landsat satellite image was more sensitive to soil moisture. The reflectance of visible and infrared bands decreases with the increase in soil moisture, while the humidity index inferred by Landsat satellite images increases.

It follows that preprocessed images were first made with Tasseled Caps. As a result, the humidity index was chosen. Principal component analysis was performed on the images that were calculated by the humidity index. She et al. (1997) [44] and Dong et al. (2014) [45] proposed that Principal Component Analysis (PCA) could better enhance understanding of the characteristics of the humidity index based on the processed images. The gray degree of the images in subsequent processing was stretched integrally to 0–255, and density segmentation was made. Then, the sites of water bodies and wetland swamps throughout the year (hereinafter referred to as the wetland) and the fish pond and freshwater aquaculture in the area were extracted. Due to the significant differences in characteristics of these zones and based on the results presented in the section above, a remote sensing texture was adopted to distinguish between two types of wetlands, namely the wetland and the aquiculture site. The information extraction from the area was deemed sufficient, as shown in Figure 10.

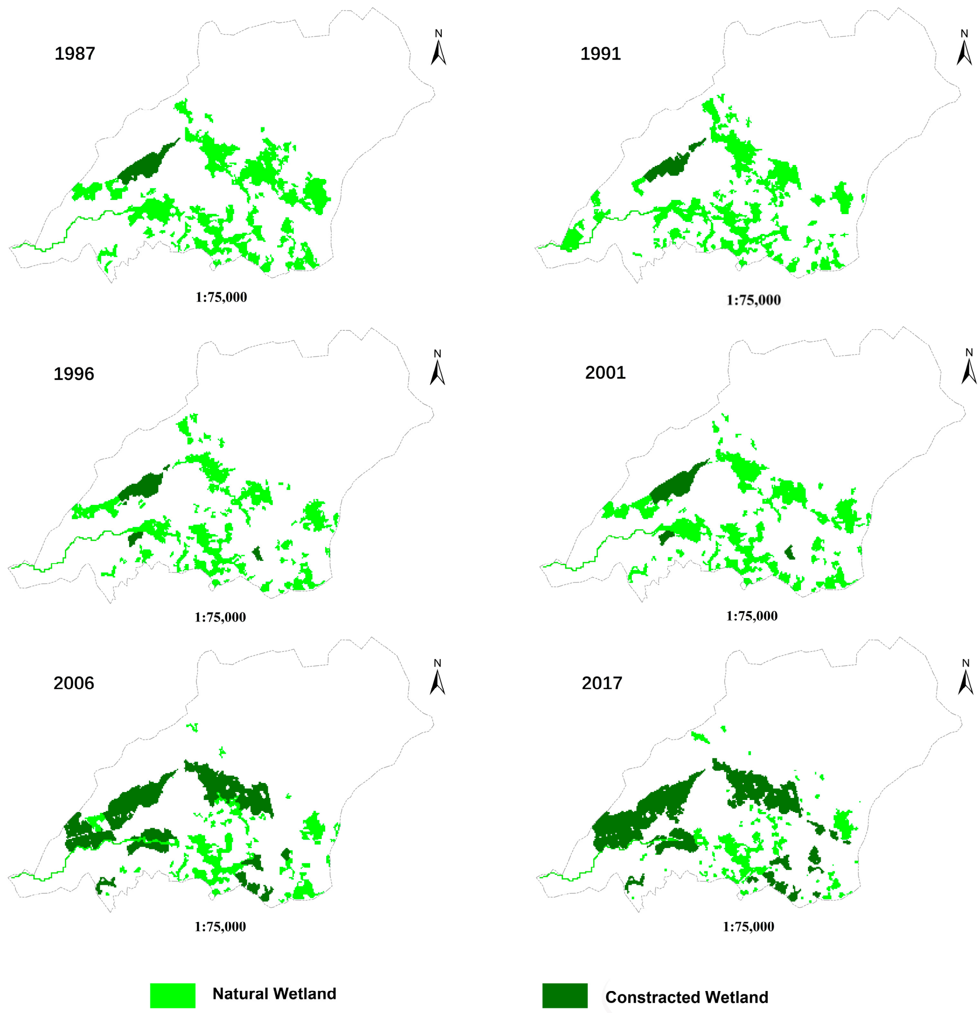

Figure 10. The results of the wetland and constructed wetland from RS image interpretation during the period from 1987 to 2017.

3.4. Numerical Simulation

Based on the above understanding of the regional hydrological characteristics, a numerical model was used to reconcile the hydrogeological conceptual model, which was used to verify the conceptual understanding of local hydrogeological settings and determine the volume of utilizable water in question. Although the hydrogeological condition of the area was complex, the terrain was relatively flat with a slight depression and poor overall permeability due to lake bottom deposits, which provided good water storage conditions. In addition, there were few boreholes recorded in the area, which rendered insufficient data required for 3D numerical modeling. Considering the purpose of this study, the area can be simplified as an equivalent continuum to address the scientific problem reported in this paper. A simple two-dimensional (2D) groundwater flow model was configured accordingly. The model boundaries were delineated based on geological maps and field verification surveys. The Guguiliu Canal was set to the south of the boundary. The west branch of Guguiliu Canal was Specific Head, whereas the east branch was Drainage. The other was No Flow Boundary. Within the simulation domain, Mudong River was generalized to a River Boundary; Fenshui Pond and the drainage channel from Fentang Canal in Mamian village in the northeast were generalized to drainage. Lake Mudong is represented by Lake Package.

To simulate the dynamic conditions of the area, including the groundwater flow field, fluctuation range of the water level, and the change situation under different water supplies, three regions were recognized and divided, and different parameters were assigned for different zones as indicated in Figure 11. The mountains of the area are mainly recharge regions; the cultivated areas in the middle of the area are mainly runoff regions; and the water bodies are mainly drainage regions. There are 8 stations in the groundwater monitoring network in the area that have complete data, i.e., 5#, 6#, 9#, 14#, 15#, 16#, 18#, and 22# as indicated in Figure 3. The monitoring data were used as calibration points during the model simulation. Among them, 6 of 8 points are in the confidence interval, for which fitting differences are less than 0.5–1 m. Both the water level and the water volume were incorporated into a unified hydrological unit, and the initial relationship between the water level and the water volume is established. The resultant flow field of groundwater was consistent with the multi-year average observation, as indicated in Figure 12.

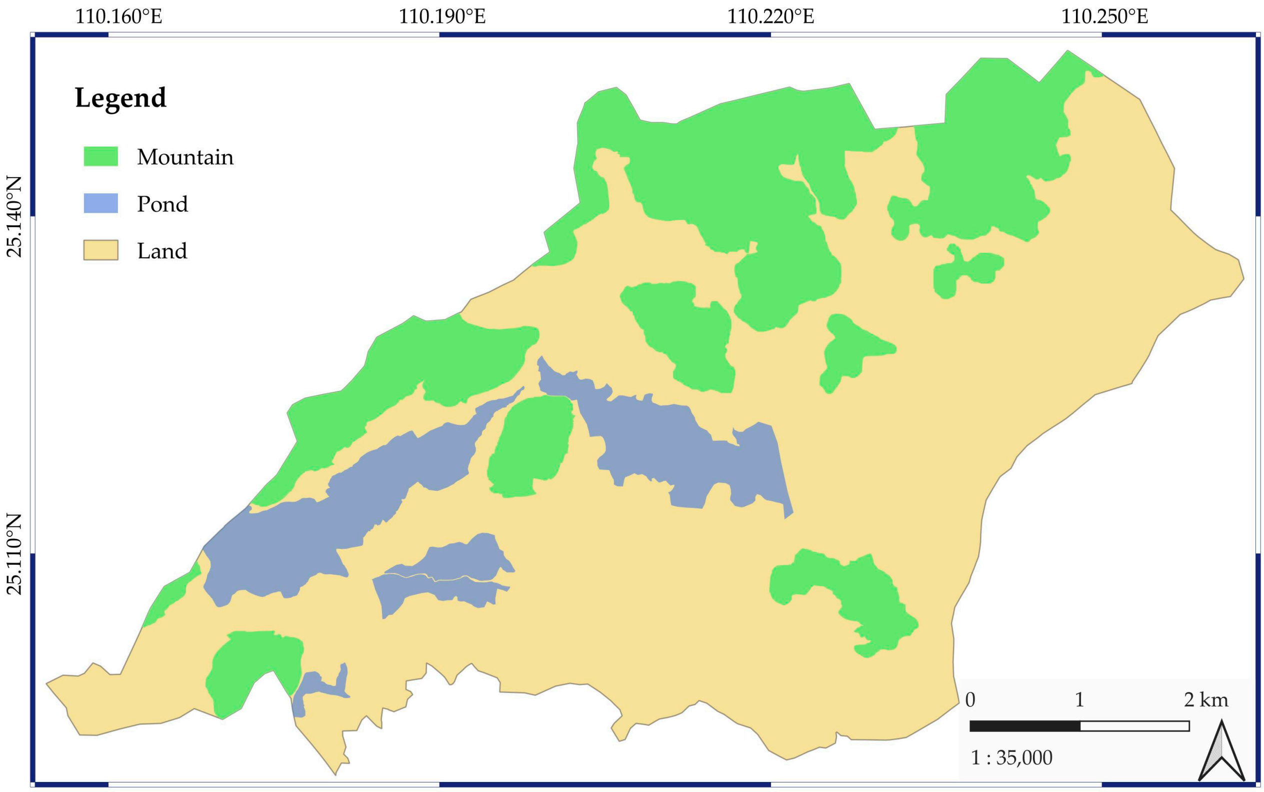

Figure 11. The situation of the divided region in the area.

The precipitations for a period from September 2018 to August 2019 at Guilin station were utilized in order to compare with monitoring data. The unsteady flow simulation of the numerical model was established with the steady-state flow field as the initial flow field. Using the monitoring data of groundwater levels, transient flow simulations were calibrated with the annual variation of water levels and water volumes of the lake estimated as shown in Table 2. The result showed that there was a significant fluctuation in the annual variation of water levels and water volumes in Lake Mudong, which is consistent with the conceptual understanding of local conditions.

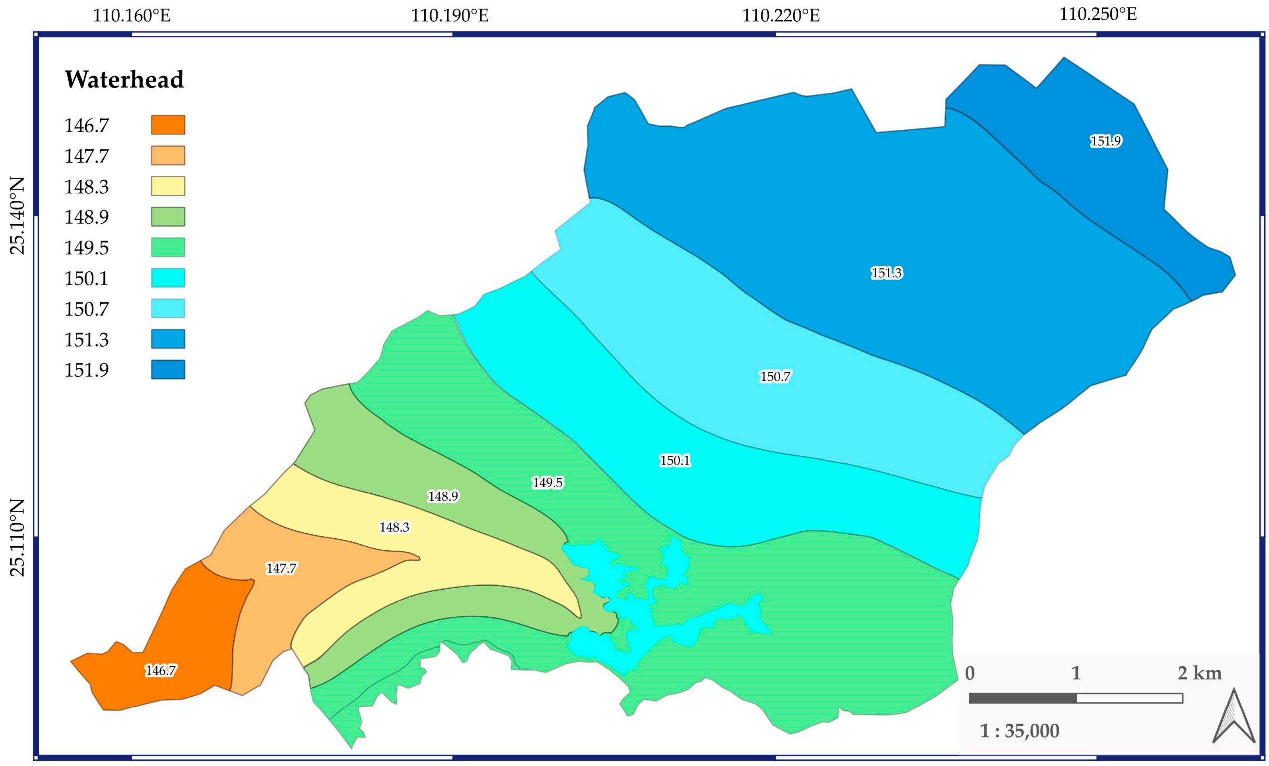

Figure 12. Numerical simulation of a steady flow field for groundwater in the study area.

Table 2. Interannual variation of water level and water volume in Lake Mudong (the reference water level is 148.20 m).

Time	Water Level (m)	Lake Storage (Million m^3)
September 2018	148.20	19.49
October 2018	148.39	19.57
November 2018	148.33	19.55
December 2018	148.36	19.56
January 2019	148.18	19.48
February 2019	148.25	19.51
March 2019	148.34	19.55
April 2019	148.59	19.65
May 2019	148.68	19.69
June 2019	148.38	19.57
July 2019	149.85	20.17
August 2019	149.07	19.85

4. Results and Discussion

4.1. Hydrological Characteristics of the Wetland

In the water balance analysis, the independently assessed components in the area were summarized as follows: the precipitation of 91.85 million m^3 (P) and the combined volume from both evapotranspiration and runoff of 86.81 million m^3 (E + R). The difference between P and E + R was 5.04%, a marginal error, as indicated in Figure 13.

It was shown that the water budget of the Lake Mudong zone is basically in balance. Hence, it is valid to assume that the flow routes or circulation patterns of the wetland in the watershed area are mainly driven by precipitation and the horizontal runoff in the form of karst water and lake-river flow, which initially flowed from both the north and the south towards the center, and then from the center it was diverted towards the east and west discharge points. At the scale of the problem involved, the component of large regional vertical groundwater circulation could be neglected (5.04%) in the area (Figure 2).

This determination is in agreement with the field observation, forming a basis for further assessing the wetland. This implies that the deep circulation of karst systems through deep leakage was necessarily ignored in the area. Meanwhile, water balance analysis also reflects the stability of Lake Mudong zone storage, which could maintain the ecological environment of the wetland. Therefore, that observation could inform further study for regional sustainable development of the area. The final determination of the availability of water resources would be made based on this premise.

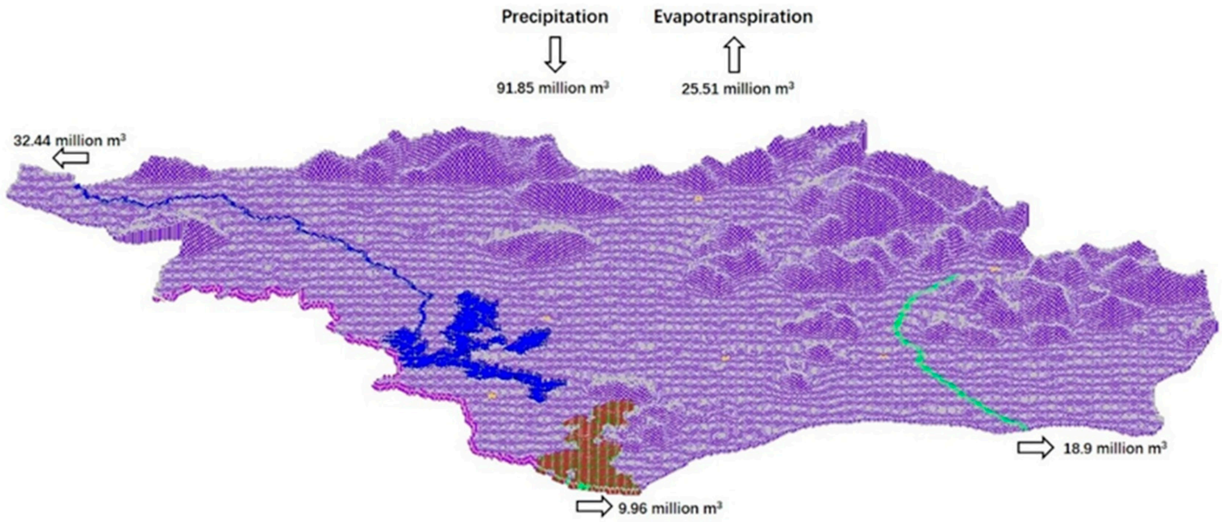

Figure 13. Diagram of the result of the water balance analysis over the area.

Based on this premise, remote sensing data were acquired and analyzed to understand the evolution of the area over the years. The accuracy of the inferred results is evaluated by Worldview 2 high-resolution images over the target area and field wetland surveyed data. In the end, the overall accuracy of the whole wetland extracted result was up to a confidence level of 95.88%, and the Kappa Coefficient was 0.8296, which indicates that the recognition result was in good agreement with the true condition of Huixian wetland. Then, the natural and constructed wetland and Lake Mudong were distinguished by the vistal inspection.

In addition to the above information obtained from RS, three aspects were considered, namely the precipitation data obtained from the Guilin hydrometric station, the population expansion from the Statistical Yearbook of Guangxi Zhuang Autonomous Region, and the local stimulus policies launched by the government. Spatial analysis of GIS was required for the identification, comparison, and analysis of the hydraulic dynamics of Lake Mudong, the wetland, and the constructed wetland over the past 30 years. The following points were noted:

Results from 1987 to 2017 showed no particular trend of precipitation, and the wetlands were observed in general, as indicated in Figure 14a. However, variations in wetland sizes had been synchronized with rainfall fluctuations until 1999. It can be seen from Figure 14b,c that the local population and the freshwater aquaculture in Lingui Town grew steadily. The local government launched stimulus policies for structural readjustment of the rural industry during the late 1990s. Freshwater aquaculture had increased sharply within a short space of time, while the area of the wetland concomitantly shrank significantly.

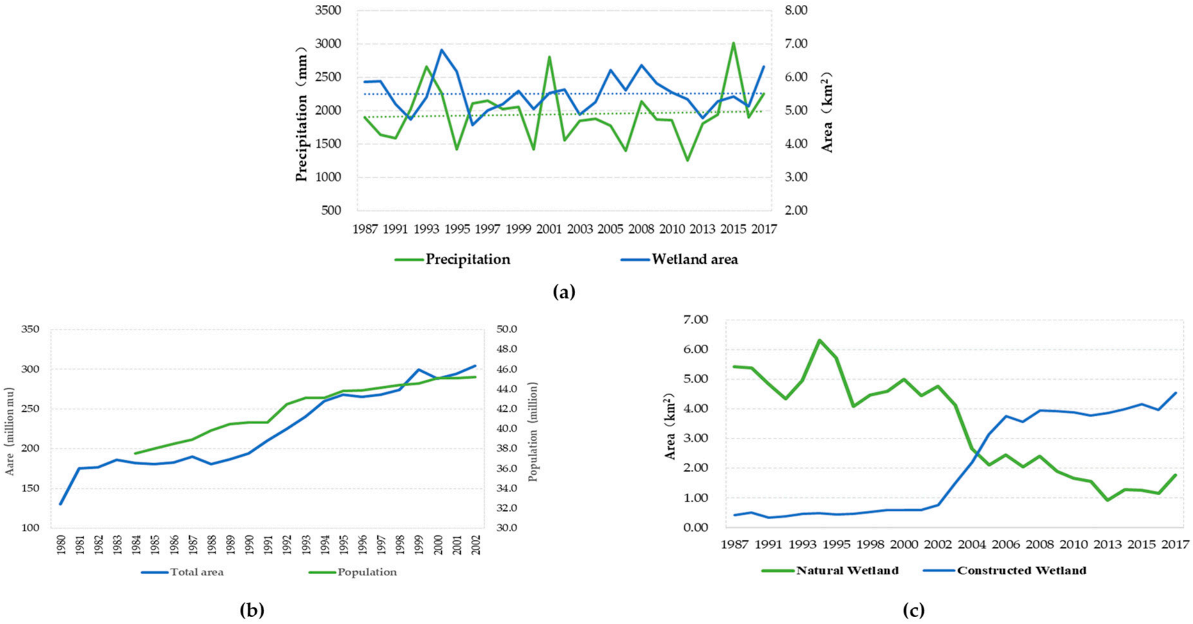

Figure 14. Change trends with the precipitation and the population of the area: (**a**): Change trends of area and precipitation; (**b**): Total area of the freshwater aquaculture and the population of Lingui Town; (**c**): Change trends of the water surface area.

To analyze scenarios over the area for 30 years, information on RS was analyzed by the GIS platform (Table 3). It is shown that Lake Mudong suffered heavily from shrinkage by 55.98% overall, and the remainder of the wetland was almost developed into a fishpond or farmland during the period from 1987 to 2017.

Table 3. The variational situation over this study site during the past 30 years.

Name	**Square(km^2)**		**Variational Situation**
	1987	**2017**	
Lake Mudong	1.11	0.49	shrank 0.62 km^2
the Wetland	5.16	1.4	3.76 km^2 transform to ponds or farmland
Constructed Wetland	0.95	3.67	Increased 2.72 km^2

On the one hand, the wetland size could vary with the rainfall fluctuations available in the natural conditions. On the other hand, with the intensification of human activity locally, the natural flow regime was altered accordingly. Among the factors influencing the evolution process of the karst wetland, human activity became particularly influential. Yet, the results showed that the hydrological characteristics of the low-lying region of the area were conditioned by not only local karst water retention but also the regional precipitation intensity. According to the analysis of the health conditions of the area, the health class for it was estimated at Level III, sub-health status, which indicated that the natural health of the wetland was modified to some extent, with some habitats damaged to some degree due to local development [46]. The ecosystem still has its basic function but is vulnerable. Huixian wetland had been evidently modified by local anthropogenic development. The results from the RS and GIS confirmed the observed hydrological characteristics of the wetland and its sensitiveness to human disturbance.

Subsequently, the layer of information from RS about Lake Mudong over many years and regional DEM were superimposed, and the water levels and sizes of Lake Mudong showed a strong correlation over multi-year and interannual periods, as indicated in Figure 15a,b. The water level fluctuation exerted control over the areal variability of Lake Mudong. By comparing the water level obtained by Landsat 8 OLI satellite images with the measured data during the same time in 2018, the error incurred between the two were 0.5 m, and the wetland water level obtained through RS is deemed realistic. Their agreement provides theoretical support for the methods adapted for assessment in the area.

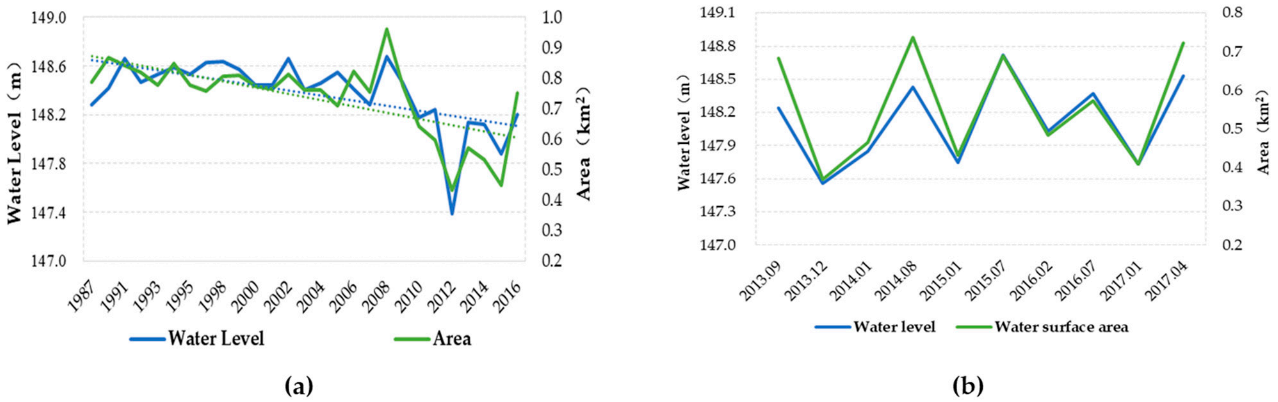

Figure 15. The relationship between water level and area of Lake Mudong; (**a**) the changing trend during the period from 1987 to 2017; (**b**) the seasonal variation situation in many years.

As the largest karst lake in the area, the fluctuation of the water level of Lake Mudong directly reflected the amount of karst water flux within the ecological environment on a local scale and influenced the aquatic vegetation ecosystem of the area. During the long-term evolution process, aquatic vegetation gradually shaped morphological features that could adapt periodically to water regimes [47,48]. The aquatic vegetation ecosystem surrounding Lake Mudong was used as an indicator to determine if the water level dropped below the requirement. Emergent aquatic vegetation (EAV) and submerged aquatic vegetation (SAV) were extracted and analyzed using Landsat images and GIS for 30 years. With the Huixian wetland modified strongly for the fishery, 0.657 km^2 of the EAV disappeared, and about 63% of the vanished area of the water body was replaced by the EAV. The growth of SAV was too limited to establish a significant role as an indication. Among the local dominant species, Cladimu chinense Nees and Typha Angustata, the former is particularly prominent. The range of tolerance of Cladimu chinense Nees to water level fluctuation can be used as a constraint indicator for the water levels of Lake Mudong. According to the field surveys for Cladimu chinense Nees habitat, a critical threshold of lake water level for the emerged plant was 148.2 m in the normal period, which is the minimum water level of Lake Mudong after the available water was withdrawn from the area [49]. The water level of Lake Mudong should be carefully monitored and managed within an acceptable threshold to ensure that the wetland sub-health status will no longer get worse. There is no doubt that it is necessary to determine the potential use of karst water to respect the accepted thresholds of water level set to protect the environment that produces and stores such water for sustainability-related aspects.

4.2. Flow Regime of the Wetland

In terms of determining the available water resources, the hydrological characteristics and water flow regime of the area should be considered simultaneously. The Fenshui pond within the Guguiliu Canal, constructed in the Tang Dynasty, was deemed a fixed karst watershed postulated in the core area of Huixiain wetland. Through the field survey, however, the flow directions around Lake Mudong and Fenshui Pond were altered depending on different rainfall intensities, which resulted in no fixed watershed but a belt of drifting ones. An attempt was made to analyze the drafting behavior of watersheds by numerical simulation. With changed patterns of rainfall distribution in the model, the watershed shifted from Lake Mudong to Fenshui Pond; that is to say, the watershed of the area was verified to swing between these two places, owing to the complexity of hydrodynamics as indicated in Figure 16.

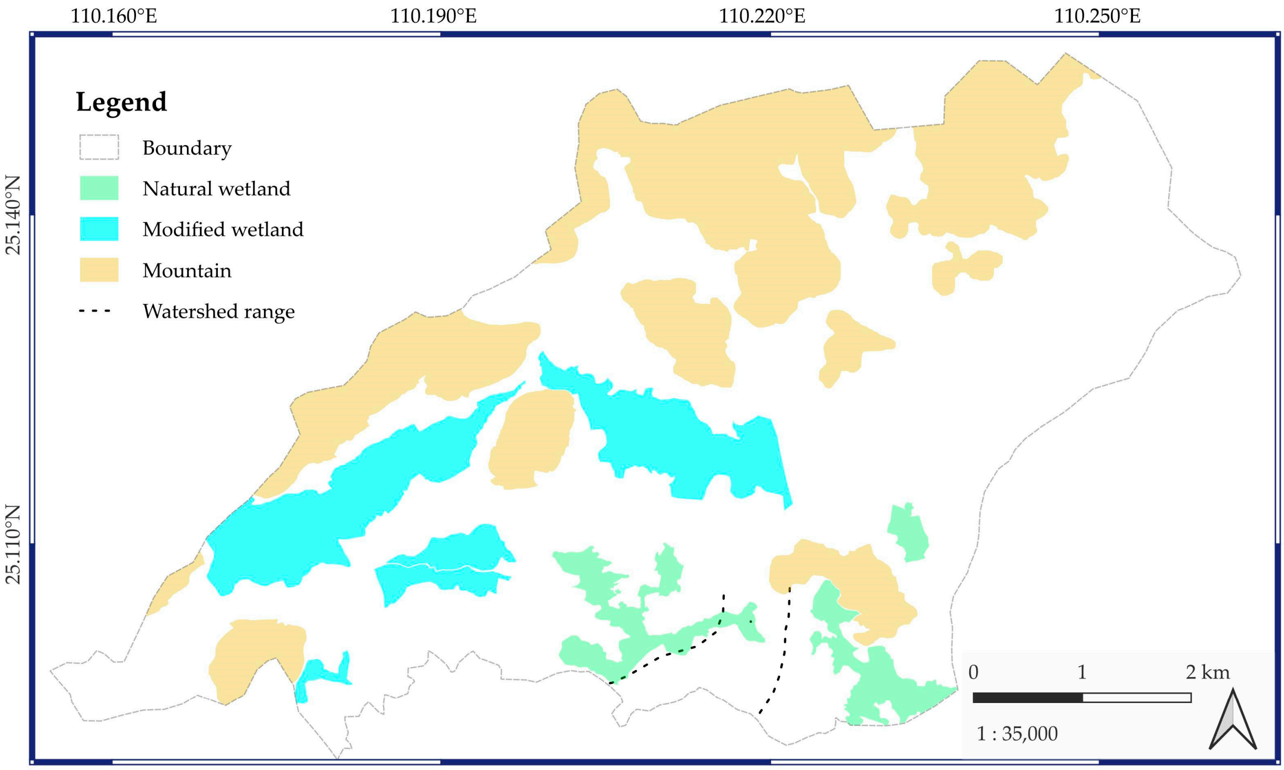

Figure 16. The dynamic range of the watershed near Fenshui Pond.

Under this condition, the scenarios for the water supply potential were considered based on the hydrologic conditions discerned in Lake Mudong through the simulation analyses. Typical scenarios of the impact of the water supply of karst water at 5%, 10%, 15%, and 20% of the precipitation recharge in the area were simulated and assessed as shown in Table 4.

Table 4. Scenarios of abstraction of inflows into Lake Mudong.

Percentage (%)	Water Supply (m^3/d)	Mean Water Level (m)	Mean Water Volume (Million m^3)
5%	712	148.29	19.53
10%	1424	148.25	19.51
15%	2135	148.21	19.50
20%	2847	148.18	19.48

If the health status of the wetland ecosystem was kept at sub-health, which is the bottom line acceptable for sustainable utilization of the karst water resource, the water level of Lake Mudong would have dropped just below the critical threshold when 20% of the recharged water with 1.04 million m^3 was withdrawn, which was determined by the EAV indicator. Adding the karst water withdrawal into the water balance for calculation kept the general balance in the whole area, and the marginal error decreased to 4.3%. That means that there was 20% karst water, which could be utilized to support the wetland development. However, the rainfall is extremely uneven, and the water level of Lake Mudong has a large fluctuation in dry and wet seasons in the area, as indicated in Table 2. The threshold should be strictly controlled. Beyond this threshold, the ecosystem health of the wetland would be problematic and would further deteriorate. Under this scenario of utilization, the impact on the annual variation of water levels and water volumes in Lake Mudong was within the acceptable margin of modification if the total water withdrawal was less than 20% of the recharged, which could keep the current wetland away from further shrinkage, and the flow regimes would remain stable within the water balance limits. And then, the different withdrawals for different periods could be considered, namely that stored water in the wet season would cope with water scarcity during dry periods.

5. Conclusions

This paper makes use of the core area of Huixian karst wetland to demonstrate that multi-methods are suitable for use in determining the available water resources at a macro level without compromising the health of the current ecosystem. The impact of water utilization on the health of the wetland ecosystem is assessed using a combined approach.

1. Based on the field investigation and water balance check, the routes of water circulation in this study area were verified in a karst wetland located in a watershed region, which implies the integrity of the wetland flow system.

2. In the absence of the long-term monitoring data sets that are measured and observed, RS and GIS techniques were used to obtain and analyze temporal and spatial data for this study area. Such analysis showed support for the available water within the framework of sustainable development. In addition, the analysis revealed that precipitation was the main source of karst water in the area. However, the wetland size in its natural state could vary in response to the fluctuations of precipitation involved. The hydrological characteristics of such an area were directly impacted by both the local karst water retention and the regional precipitation intensity. In addition, local anthropogenic activity in the vicinity of the wetland was the most relevant. The partially constructed wetland in history led to the change of flow regimes, and the excessive exploitation of karst water without a follow-up monitoring program in place was the main cause of the wetland's current shrinkage.

3. Based on conceptual modeling, a zone of mobile watersheds in a wetland catchment was illustrated as opposed to a single fixed-line watershed, while the field investigation and analysis of RS and GIS were verified. Under the established relationship between the groundwater and the lake in the model, the native dominant species Cladium chinense Nees can be used as an indicator to control the water level of Lake Mudong in order to restrict water consumption within the wetland. It was conceptually determined that the flow regime of the area would still be kept in balance under a scenario of less than 20% withdrawal. The annual variation of water levels and water volumes was the acceptable margin of fluctuation that could maintain the current wetland integrity, provided that a follow-up monitoring program was in place. Therefore, it is necessary to use ecological indicators as a constraint and guide for the wetland for its sustainable utilization, and the wetland could adapt to the changing environment under dynamic conditions.

4. In this paper, the available water resource was quantified, which could support a scientific decision-making process for local sustainable planning and development. The approaches adapted in this paper would be used to refine a working framework under which the sustainable utilization of karst water resources could be accommodated and fine-tuned where necessary. The results provide much-needed scientific information for the protection of the wetland and its sustainable water utilization, and they would offer a basic reference for the similar problems in karst areas of southwest China and other areas with similar characteristics, among others. However, due to the lack of data over a long period, the accuracy of this study area could still be improved. For the purposes of wisely using wetland resources, a comprehensive and effective monitoring strategy for the wetland should be in place, including meteorological data, the water level and water volume of Lake Mudong, and the growth status of EAV (emergent aquatic vegetation). The specialized, scientific, and unified management of wetland would provide the basis for sustainable development of the wetland.

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