

Article

A Sponge Village Flood Response Method Based on GIS and RS Analysis Formation—A Case Study of Jiangou Village

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Abstract: This study was conducted in response to the Beijing–Tianjin–Hebei mega heavy rainfall event at the end of July 2023, and the severely affected and representative Jiangou village in Beijing was selected as the study area. A variety of methods were used to synthesize and analyze the situation and propose an adaptive response to heavy rainfall and flooding in the village. Based on multi-source remote sensing (RS) data, a comprehensive topographic and hydrological characterization was carried out, and the precipitation before and after the disaster was analyzed; the flood inundation area was extracted using the improved normalized water body index (MNDWI) and OTSU thresholding methods, and the changes of water bodies during the flooding period were quantitatively analyzed; and an improved convolutional-neural-network-based building identification and extraction model was constructed to extract the research distribution of buildings in the area. The sponge city construction (SPCC) method was improved to obtain a method that can mitigate flood risk and adapt to villages by constructing small artificial lakes and local topographic buffers to improve the water storage and drainage capacity of villages. The study shows that these methods are innovative in flood hazard analysis and mitigation but still need further improvement in data accuracy, simulation depth, and system evaluation.



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Keywords: GIS; remote sensing; sponge village; flood risk management; Beijing

1. Introduction

Due to the rapid changes in the global environment, in particular the continuing rise in temperature, natural disasters have escalated in frequency and severity [1]. This is a direct consequence of global climate change, highlighting the strong link between disaster risk and global environmental change [2]. Of particular concern are floods caused by heavy rainfall, as they have a widespread and significant global impact [3]. Floods destroy infrastructure, cause significant economic losses, and have a significant impact on the global economy. This impact is seen in various sectors such as agriculture and industry [4]. As the most common natural disaster, floods have caused about 53,000 deaths worldwide [5]. In Europe, floods in 2005, 2007, and 2010 caused economic losses of more than EUR 1 billion [6]. In 2012, Beijing, China, experienced a once-in-a-century rainfall event. The average rainfall in the city was 164 mm, with localized rainfall exceeding 400 mm. According to official statistics, the storm resulted in 79 deaths and direct economic losses of more than RMB 11.6 billion, a figure that includes infrastructure damage, damage to houses and buildings, agricultural losses, and other types of property damage.

From 29 July to 2 August 2023, the Beijing–Tianjin–Hebei region experienced heavy rainfall, severe flooding, and waterlogging due to the combined effects of the residual circulation of Typhoon Dusu Rui, the subtropical high pressure, and the water vapor transport of Typhoon Kanu. In particular, on 31 July, flash floods and waterlogging severely affected the Mentougou District and Fangshan District of Beijing, as well as cities in the

plains near the Taishan Front, such as Zhuozhou City in Hebei [7]. The cumulative rainfall in Mentougou District far exceeded the '7–21' rainstorm of 2012, reaching 471.1 mm, with the maximum rainfall reaching 723 mm, the highest in the history of meteorological records and the highest in all of Beijing. The Beijing Municipal Bureau of Meteorology considers this to be the largest rainfall event in 140 years. Jiangou village was located near the point of maximum rainfall; 10 people died and 15 were missing around the village and surrounding areas; more than 100 houses were destroyed or severely damaged by floodwaters; approximately 500 acres of farmland were submerged, resulting in crop failures; a number of roads and bridges were washed away; and power facilities were severely damaged, resulting in direct economic losses of more than RMB 100 million.

As can be seen, storm water floods cause significant loss of life and economic damage every year. To address this challenge, it is very important to combine the study of hydraulics and hydrology, which are two important disciplines for studying the behavior and nature of water. Hydrology mainly studies the origin, distribution, and circulation of surface water and groundwater, while hydraulics is mainly the study of fluid in the flow process of the laws of motion and its mechanical properties. Some scholars have developed the Learning in Floods (LFF) model based on the knowledge in this field to study the learning processes in different environments and their influence on flood resistance [8]. Furthermore, studying the disaster response experiences of individuals living in different flood-resistant habitats could significantly improve flood prevention and resilience [9]. Scholars have proposed strategies to improve flood response in the middle and lower parts of the Yangtze River Basin by anticipating heavy precipitation, which is becoming more frequent and intense due to extreme weather events [10]. Furthermore, there are noticeable regional variations in the overall pattern of intense precipitation [11], necessitating the implementation of more targeted government interventions. The Chinese government has invested significantly in improving strategies to prevent and address prevalent water problems, including flooding from excessive rainfall, water pollution, and water scarcity [12–14]. This initiative aims to ensure the well-being of individuals and maintain economic stability while addressing the difficulties posed by global environmental change and enhancing the capacity to prevent and mitigate the consequences of floods.

Of the 782 extreme flash flood events documented, the most intense occurred primarily in small watersheds with complex topography. In these areas, small and medium-sized floods are the most common [15], and the occurrence of sudden floods is relatively common. Most of them are located in mountain villages, where disaster response is more difficult than in cities, and the damage tends to be more severe.

In response to flood risk, hard engineering control measures, such as the construction of flood control dams, have been favored in China for many years. By 2014, China had established the concept of the 'sponge city' to address urban surface water flooding and related urban water management issues [16,17]. The sponge city (SPC) concept is similar to the Low Impact Developments (LID) approach in the United States [18]. The sponge city aims to adopt and develop LID concepts that improve the effective control of urban peak flows, upgrade traditional drainage systems with more flood-resilient infrastructure, and increase current drainage protection standards using LID systems to offset peak flows and reduce excess storm water [19]. The SPC and LID are unable to withstand flooding effectively [20], and it is difficult to carry out applications in rural areas. To address this problem, this study adopts multiple methods to comprehensively analyze and propose an adapted response to heavy rainfall and flooding in rural areas. Based on multi-source data, a comprehensive topographic and hydrological characterization is conducted; the precipitation before and after the disaster is analyzed in combination with meteorological data; based on Sentinel-2 data, the flood inundation area is extracted using the modified normalized water body index (MNDWI) and OTSU thresholding methods, and the changes in the water body during the flooding period are quantitatively analyzed; and a convolutional neural network based on an improved building identification and extraction model is used to extract the distribution of buildings in the study area. This study takes the

principle of improved sponge city construction (SPCC) [21] as a reference and proposes a sponge rural flood response method by combining the special characteristics of the rural area while reducing the financial overhead of the rural area in terms of grass management, etc., and keeping the application function of the area unchanged. The details of this study are shown in Figure 1.

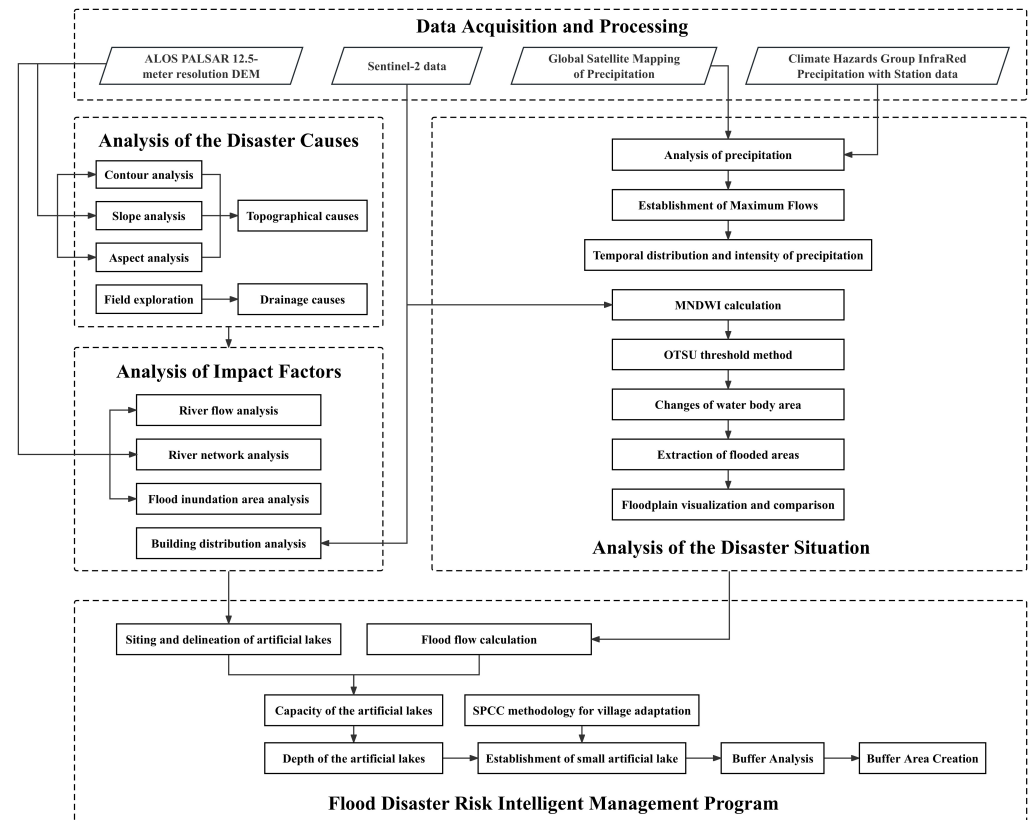


Figure 1. General flow chart.

2. Materials and Methods

2.1. Overview of the Study Area

The area selected for this research is Jiangou village, located in Miaofengshan Township, Mentougou District, Beijing, as shown in Figure 2. Jiangou village was built in the Liao Dynasty, has a history of thousands of years, and is located in the northeastern part of Mentougou District. Because the village site is located at Miaofeng Mountain within the East Gully, North Gully, and West River Gully, a three-gully confluence, the village was called ‘Sanchuanjian’ and then renamed Jiangou village in 1943, a name which has been used since then. Jiangou village covers an area of 11 km² and has a population of 305 households and 505 people.

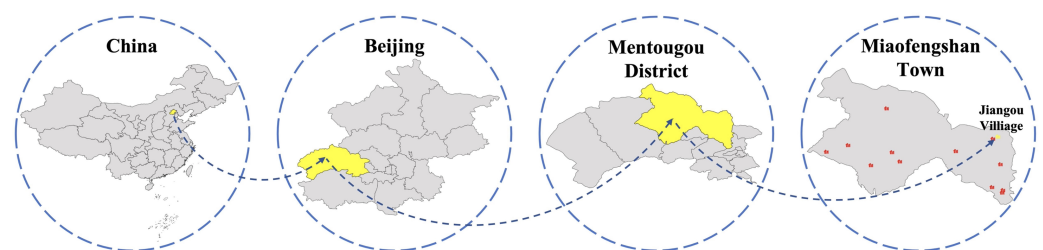


Figure 2. Location analysis of Jiangou village.

Jiangou village is located in a geographically unique area, in a mountainous region with steep slopes. The geological structure of the area is relatively complex, consisting mainly of granite, gneiss, and other rocks that are relatively hard and mostly surrounded by sloping mountains. Geographical factors influenced the occurrence of large-scale flooding and landslides during the July 2023 disaster, which trapped many people and caused severe economic losses to the village.

A cartographic representation of the regional infrastructure was created using data from the Open Street Map (OSM) (Figure 3). Villages are located at higher elevations, usually between 500 m and 1000 m. The highest point may exceed 1000 m, while the lowest point may be around 500 m. The rivers in Jiangou village have a meandering pattern, with buildings constructed predominantly along their banks, resulting in a village layout based around the confluence of the water flow. While this arrangement provides residents with an accessible source of water for their daily needs, it also makes the village vulnerable to flooding during severe weather events. Throughout its history, Jiangou village has experienced numerous devastating floods, primarily caused by prolonged periods of intense rainfall. These floods occur when the water level of the river quickly exceeds the capacity of the riverbanks, resulting in varying degrees of property damage and casualties.



Figure 3. Overview map of the study area.

2.2. Data Acquisition and Processing

2.2.1. Topographic Dataset

Digital Elevation Models (DEMs), containing the basic data for describing ground elevation information, are widely used in studies of topography and geomorphology, soils, geohazards, climate and meteorology, and hydrology [22]. In this study, 12.5 m resolution ALOS PLASAR DEM data accessed through ASF DAAC (<https://asf.alaska.edu>) (accessed on 10 April 2024) were used, processed, and cropped (Figure 4) for the subsequent hydrological analysis of Jiangou village based on topographic data to model surface water flow, and these high-resolution DEM data are crucial for flood hazard analysis compared with other commonly used open-source DEM data (SRTM 90 m [23], SRTM 30 m [24], ASTER-GDEM 30 m [25], etc.); the resolution is higher and provides more accurate topographic elevation information, which is more suitable for the analysis of small villages such

as Jiangou village, and better analyzes the internal topographic structure of the village as well as its hydrological situation.

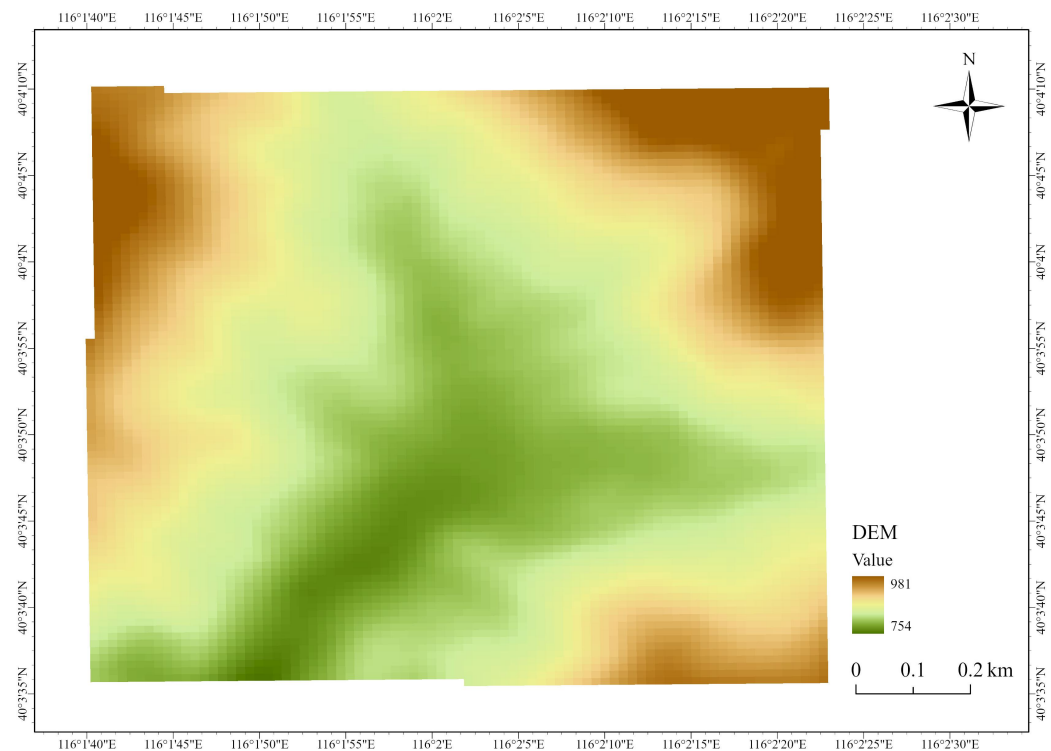


Figure 4. DEM of Jiangou village.

2.2.2. Meteorological Dataset

Since Jiangou village is a small village in the Miaofengshan Township, Mentougou District, Beijing, and there are no corresponding meteorological stations in its vicinity, it is difficult to obtain accurate historical meteorological data. Global Satellite Mapping of Precipitation (GSMaP) [26] data and Climate Hazards Group InfraRed Precipitation with Station Data (CHIRPS) [27] were selected to analyze the precipitation before and after the disaster in this study area. Both datasets were obtained and processed based on the Google Earth Engine platform, and detailed information about the data is shown in Table 1.

Table 1. Details of the research datasets.

Datasets	Resolution	Band	Units
Global Satellite Mapping of Precipitation	11,132 m	hourlyPrecipRate	mm/h
Climate Hazards Group InfraRed Precipitation with Station Data	5566 m	precipitation	mm/d

GSMaP is a product of the Global Precipitation Measurement (GPM) mission, which provides global hourly precipitation with a resolution of 0.1×0.1 degrees and is suitable for global large-scale calculations. CHIRPS provides daily precipitation data covering the entire global surface with high spatial resolution, combining multiple data sources, including weather station observations, satellite remote sensing data, and climate model data, to improve data accuracy and global coverage. The spatial resolution of GSMaP is lower but the time resolution is higher than hourly, while CHIRPS is higher in spatial resolution but the time resolution is only daily. Therefore, the two types of dataset were selected for analysis together, as they can complement each other.

2.2.3. Sentinel-2 Dataset

Sentinel-2 is a wide-swath, high-resolution, multispectral imaging mission that supports Copernicus land monitoring studies, including vegetation, soil, and water cover monitoring studies, as well as inland waterway and coastal monitoring.

Based on the Google Earth Engine platform and using Harmonized Sentinel-2 MSI: Multi Spectral Instrument Level-2A data, the calculation of the water body index and the extraction of water bodies in the area of Jiangou village before and after the flood disaster were carried out, respectively, and a comparison was made based on the results combined with the actual analysis. First, the QA 60 band (60 m resolution) was used to remove the atmospheric clouds on the image to obtain more accurate and clear data, and then the B3 (green) (10 m resolution) and B11 (SWIR) bands (20 m resolution) were mainly used to calculate the water body information for disaster analysis.

In addition, because the existing building extraction dataset made it difficult to obtain accurate building distribution data in the Jiangou village area, which affected the subsequent study and construction of the artificial water diversion system, we created a dataset with Sentinel-2 data consisting of remote sensing photos of 39 villages located in different metropolitan zones of Beijing for training and testing building recognition extraction models. Of the total, 25 villages were used as training datasets, while the photos of another 14 villages served as test datasets. Figure 5 shows the spatial arrangement of the villages.

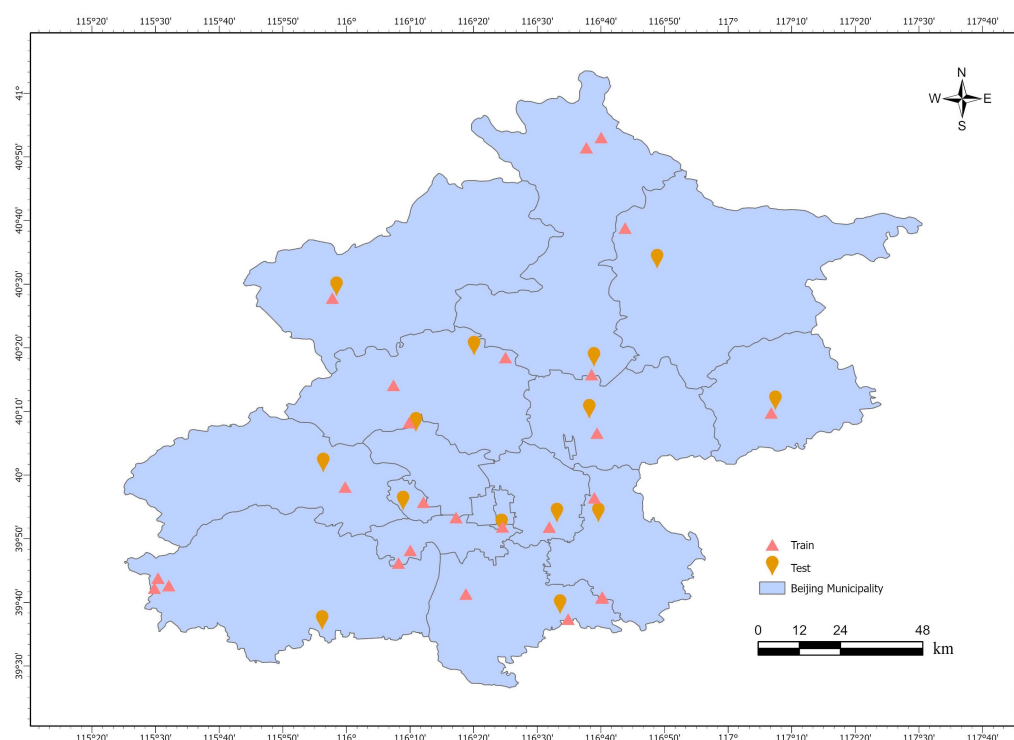


Figure 5. Map of the dataset selections.

2.3. Analysis of the Causes of Disasters

Based on the 12.5 m DEM data of Jiangou village, contour analysis, slope direction analysis, and slope analysis (Figure 6) were conducted, respectively, which could comprehensively understand the topographic characteristics of Jiangou village, and it can be seen from the analysis results that Jiangou village is located at the confluence of three ravines and has a high elevation. The elevation difference between its interior and the surrounding mountains is more than 150 m, and the slope is steeper. The general slope is between 15 and 30 degrees, and, in many areas, it exceeds 30 degrees. In addition, the slope direction of Jiangou village is varied, and the specific slope direction varies from place

to place due to the influence of topography. Since floodwaters usually flow along the terrain from high to low, the degree and direction of slope of the terrain allowed us to infer the likelihood of flood convergence areas and the direction of water flow. Therefore, based on the results of the analysis, we were able to identify potential hazard areas and infer flood routes, important flood prevention information for Jiangou village. With this valid information, village planning can better determine which areas should be left in their natural state or used as flood buffers and where construction can avoid or mitigate the effects of sudden disasters.

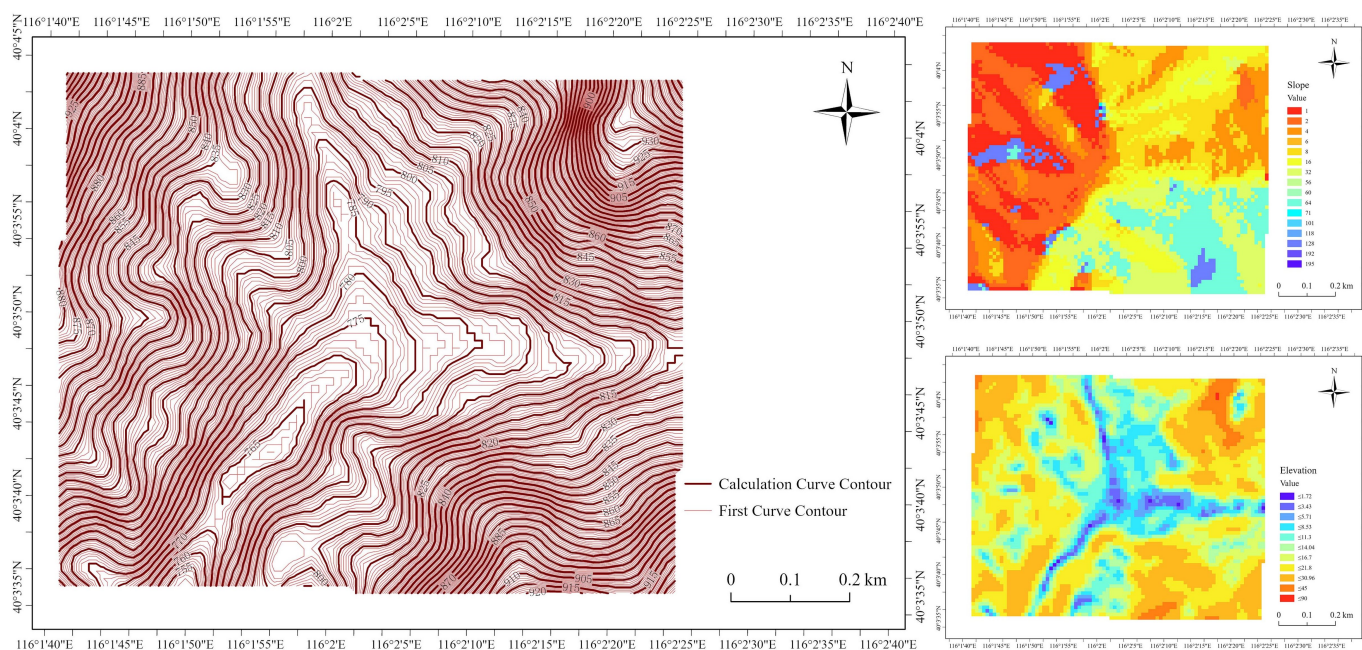


Figure 6. Topographic characterization map.

After field investigation, it was found that the water management facilities, including the drains along the roads in the central area of Jiangou village, have been exposed to sunlight, rain, and wind for a long time. As a result, they have suffered various adverse effects and have deteriorated significantly due to inadequate use and maintenance. The inadequate design and capacity of the drainage system have not kept pace with the growth of the village, resulting in an inability to efficiently manage significant amounts of storm water during heavy rains. The inadequate drainage capacity is highly susceptible to flooding during severe weather conditions, especially during intense rainfall. Flooding poses a significant risk to the lives and property of villages while having a profound impact on the local natural environment and socio-economic development. Therefore, it is imperative for Jiangou village to immediately upgrade and improve its drainage infrastructure to increase its resilience to severe weather conditions and ensure the well-being of its people and the long-term development of the region.

2.4. Disaster Situation Analysis

2.4.1. Analysis of Precipitation

According to the data released by the Beijing Municipal Bureau of Meteorology, from 20:00 on 29 July 2023 to 07:00 on 1 August 2023, the average rainfall in the Beijing Municipal area was 260.0 mm, with an average of 235.3 mm in urban areas, of which the average of 471.1 mm in Mentougou District was the largest in the city (Figure 7). In addition, there were two stations in the city with accumulated rainfall over 700 mm, namely, Changping Wangjiayuan Reservoir with 738.3 mm and Mentougou Alpine Rose Garden with 723.0 mm. The Mentougou Alpine Rose Garden station is only 500 m away

from Jiangou village, so it can be seen that the area of Jiangou village is particularly affected, and it was worth paying attention to this in the study.

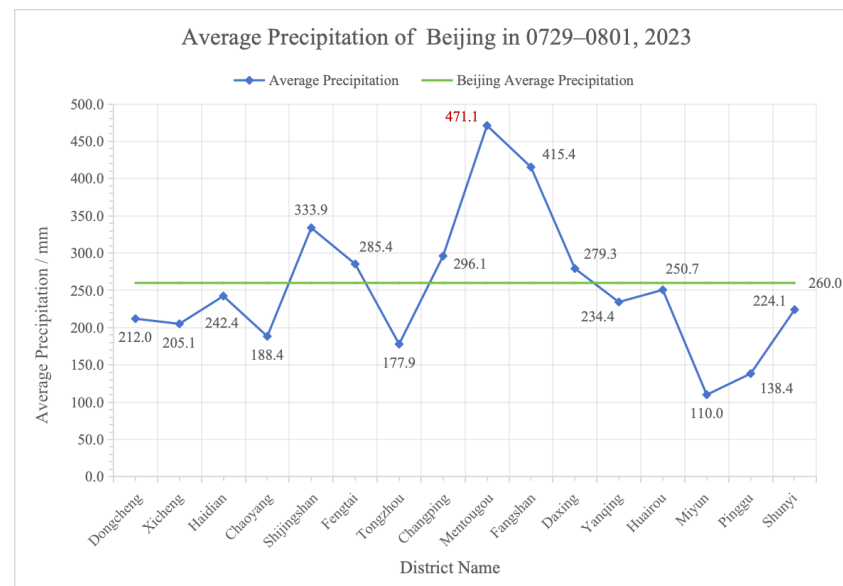


Figure 7. Average precipitation of Beijing in 0729–0801, 2023.

Due to the difficulty in obtaining historical data from meteorological stations, two types of data, GSDaP and CHIRPS, were selected for the analysis of precipitation before and after the disaster in the study area, and the two datasets were extracted for the analysis of precipitation data for the period of 20 July–10 August 2023. The GSDaP data included the hourly precipitation data, which, after summation and processing, were compiled as daily data so as to be compared with the CHIRPS data for comparative analysis (Figure 8). Combined with the actual situation, it can be seen that, although there are some differences between the two types of data, the overall trend is basically the same, and the maximum amount of precipitation for the period of 30–31 July is in line with the actual situation; therefore, the analysis results have reference value.

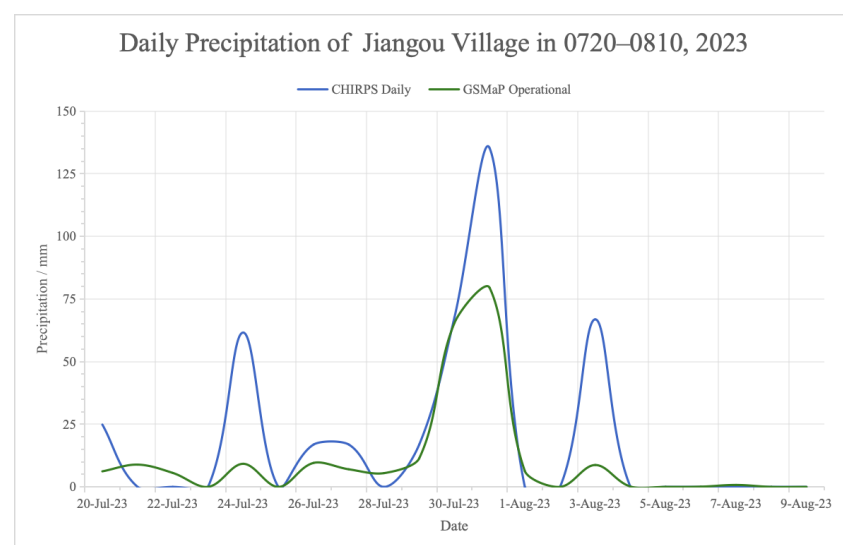


Figure 8. Daily precipitation of Jiangou village in 0720–0810, 2023.

2.4.2. Extraction of Flooded Areas

In this study, based on the Google Earth Engine platform, Harmonized Sentinel-2 MSI: MultiSpectral Instrument Level-2A data were used to calculate the water body index and extract the water bodies in the area of Jiangou village before, during, and after the flood disaster. After clouding the data, the B3 (green) (10 m resolution) and B11 (SWIR) (20 m resolution) bands of these data were used for the calculation of the modified normalized difference water index (MNDWI). The results of the calculation are shown in Figure 9a,c,e and were based on the following equation:

$$MNDWI = (B3 - B11) / (B3 + B11), \quad (1)$$

MNDWI [28] is obtained by improving the NDWI [29], which is able to weaken the influence of soil and buildings and better de-emphasizes the shadow of buildings. After obtaining the MNDWI data, the OTSU thresholding method [30] was used to calculate the water body index threshold to obtain the water body inundation mask to extract the water body area. The optimal threshold value calculated by the OTSU method in this study was about -0.22 , and the water body area before, during, and after the disaster thus extracted is shown in Figure 9b,d,f.

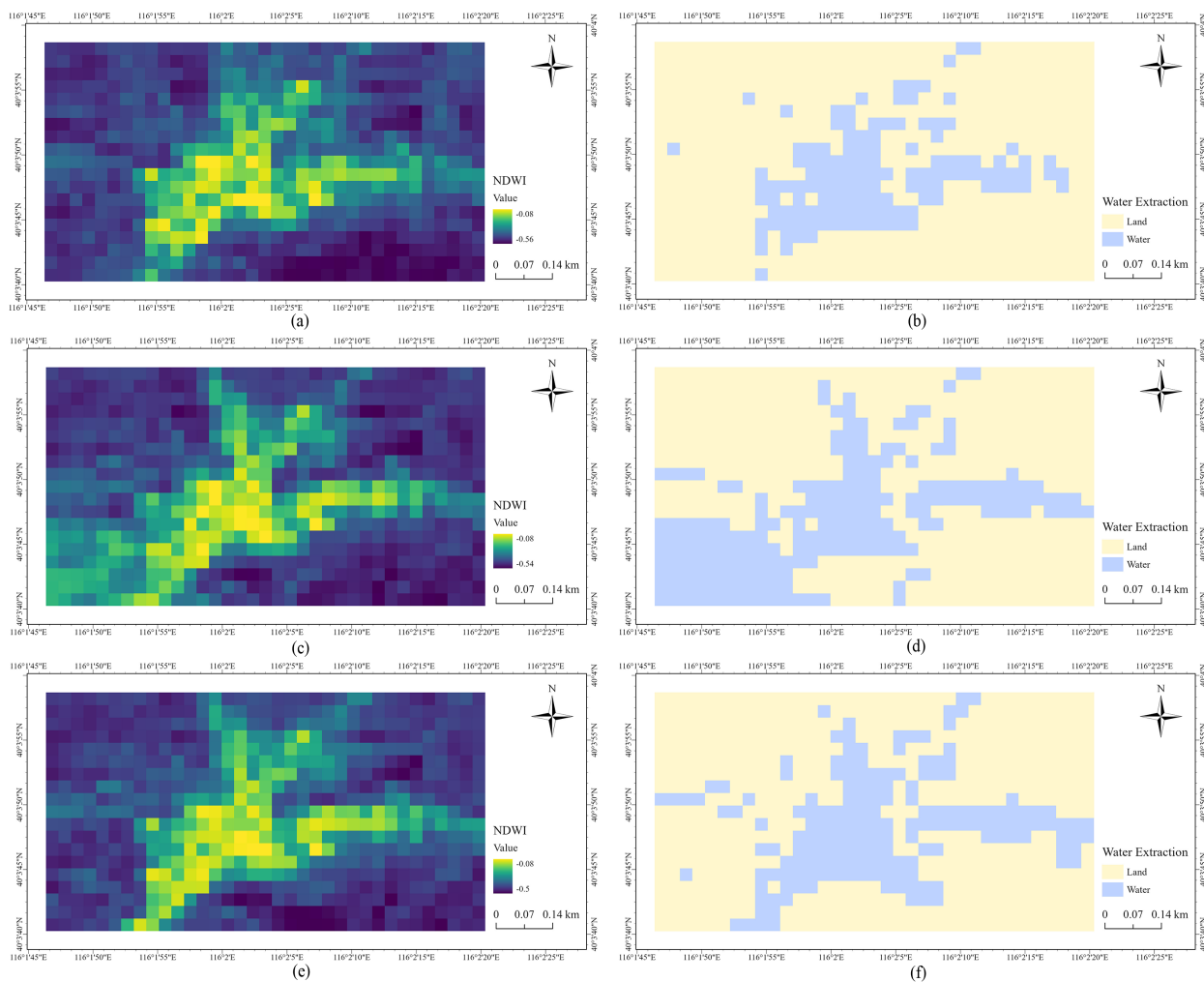


Figure 9. MNDWI and water extraction of Jiangou village before, during, and after the disaster: (a) MNDWI before the disaster; (b) water extraction before the disaster; (c) MNDWI during the disaster; (d) water extraction during the disaster; (e) MNDWI after the disaster; (f) water extraction after the disaster.

In order to analyze the severity of the flood disaster and perform further quantitative analysis, the area of the water body and the difference between pre-disaster and during disaster areas were calculated by converting the same metric area unit to square kilometers, which obtained a pre-disaster area of the water body of about 7.99 km², an area of the water body of the disaster of about 12.23 km², and an expansion during the disaster period of 4.24 km². In order to more intuitively demonstrate the change in the area of the water body, that is, the flooded area, of the Jiangou village area during the storm flooding disaster, the change in the area of the water body was combined with the above analysis results of the water body extraction for the area of visualization and comparison (Figure 10). The results show that the southwestern region experienced the most serious inundation, and, combined with the analysis of the topographic situation, it can be seen that the southwestern part of the ravine of the terrain is relatively low, the mountain slopes are larger, and it can easily become the area of water flow convergence. During heavy rainfall, the water flow on the mountain quickly converges into the gorge, increasing the amount of water and the speed of water flow in the gorge, causing the water level in the region to rise and form floods. In addition, the central area of Jiangou village has the lowest terrain, making it the main area affected by the flood. Houses were flooded, farmland was severely damaged, and most residents were forced to relocate. In the most severely affected area, the water depth reached more than 1.5 m, severely affecting residents' lives and causing severe property damage.

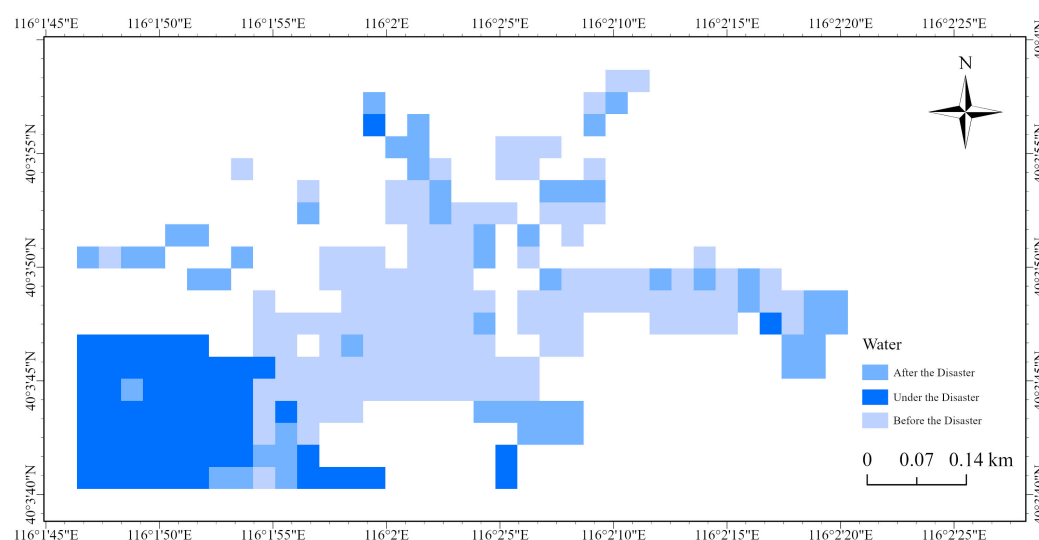


Figure 10. Comparison of water extraction.

2.5. Analysis of Impact Factors

2.5.1. Flow Analysis and River Network Classification

Flow analysis is based on DEM data, which can be used to extract the features of water bodies in regional rivers under normal conditions. This serves as a basis for studying variations in flow under different circumstances. The classification of river networks is determined by criteria such as the magnitude of the river flow and its influence on the surrounding region. This process involves categorizing and ranking the river system to distinguish the primary river from smaller tributaries. The primary river typically has a larger volume and a wider sphere of influence, requiring special monitoring and management efforts. Although smaller, tributaries can have significant local impacts during extreme weather events such as heavy rainfall. Therefore, it is important to focus on the monitoring and management of these tributaries. In addition, these studies can accurately monitor and predict the origin of floods and their evolving patterns, providing comprehensive data for potential disaster mitigation and response.

Figure 11 shows the study of river flow and river network grading in the Jiangou village area. During periods of intense rainfall, the substantial increase in rainfall in the area where water is collected and drained usually results in a rapid increase in the volume of water in the river. Due to the flat terrain of Jiangou village, river water accumulates in the central area, resulting in flooding that spreads outward in a radial pattern, causing widespread flooding. In addition, the rivers around Jiangou village are part of a lower-level river system, which means that their water-carrying capacity is limited. Under severe weather conditions, these rivers cannot adequately manage and regulate the flow of floodwaters, resulting in rapid flooding that can quickly submerge surrounding areas.

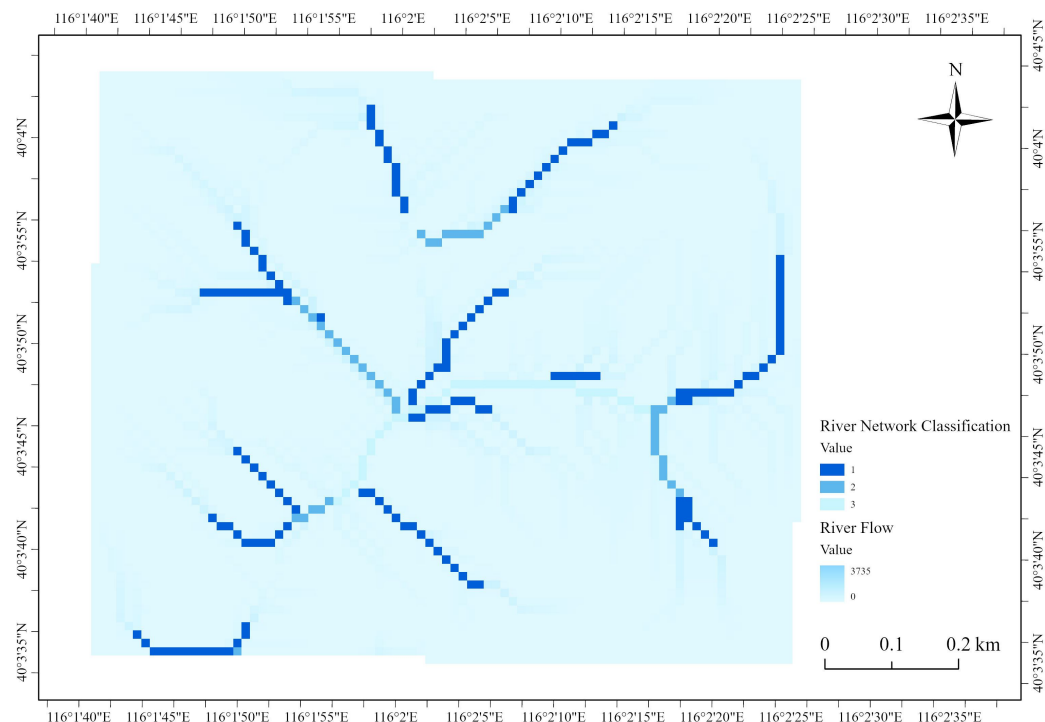


Figure 11. Flow and stream network hierarchy map.

In conclusion, the extensive flooding of Jiangou village caused by the sudden increase in river flow is not a random event but an unavoidable result caused by multiple circumstances. This demonstrates the urgent need to build a diversion area in the village.

2.5.2. Building Distribution Analysis

To enable better land use and planning for villages and townships, it is necessary to determine the area covered by buildings and their density; therefore, automated building mining is essential to accurately assess flood risk in densely populated areas. By determining the exact location and extent of buildings, we can better predict potential damage and develop appropriate flood management strategies. Convolutional neural networks perform better in a variety of scenarios [31]. A method for identifying village structures from high-resolution remote sensing (HRRS) photographs has been proposed. This approach uses an enhanced convolutional neural network (ECNN) [32]. The methodology used in this study involves first performing Faster R-CNN target detection on the designated area, followed by cropping the image blocks of the buildings. Then, the PolygonRNN algorithm is used for building detection. By combining these two algorithms, the extraction accuracy is improved, and the requirements of planning and design are better met.

After conducting comparison experiments with the ECNN method, the results obtained (Figure 12) indicate that, while the ECNN method allows for fast recognition of rural buildings, it struggles with the presence of unclear edges in remote sensing images. Lighting, shadows, color similarity between buildings and the background, limited res-

olution of remote sensing images, weather conditions, and clutter are the main causes of these blurred edges. On the other hand, the PolygonRNN method approximates the building outline by generating polygons. This approach emphasizes the overall shape of the building rather than focusing only on the edges. This approach is more resilient to edge ambiguity because it does not depend only on edge information but also considers the geometric characteristics of the structure. Thus, PolygonRNN showed superior accuracy compared to ECNN in the specific rural complex scenario of this study.

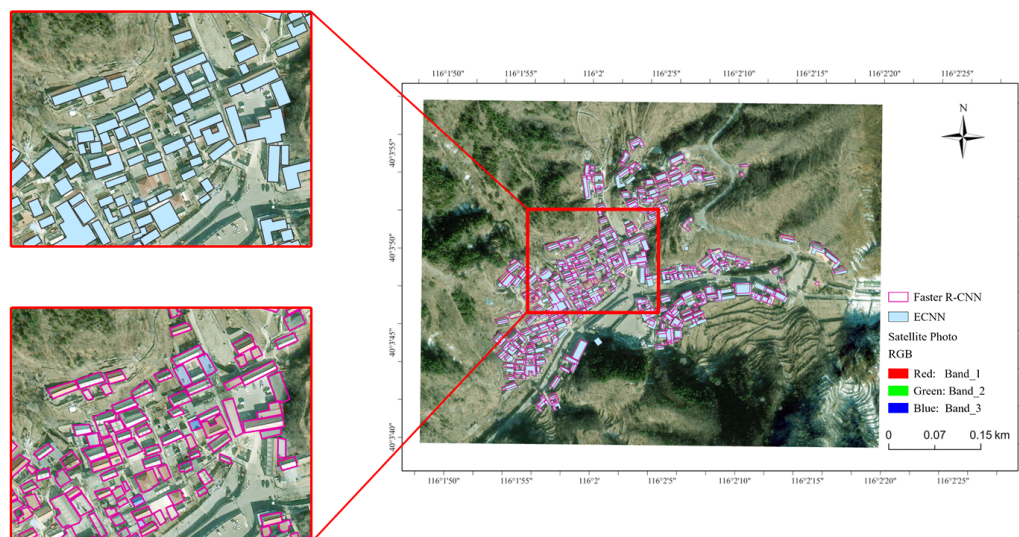


Figure 12. Comparison of the results of Faster R-CNN combined with PolygonRNN method and ECNN method.

2.5.3. Flood Inundation Area Analysis

DEM was used to create an ArcGIS terrain model, which was the basis for the inundation study. The spatial analysis capabilities of ArcGIS were used to examine potential water flow paths and areas that may be submerged at different water levels.

Using the terrain model, the approach could accurately predict the extent of flooding under different water level scenarios. The simulation analysis conducted at various levels showed that the flood disaster was a comprehensive disaster resulting from the convergence of central and external floods. Jiangou village is vulnerable to both internal and external flooding during heavy rainfall. The primary objective of the research area should be to explore methods for implementing drainage diversion in the central region of the village.

Rainfall simulations were conducted for Jiangou village with rainfall amounts of 10 mm, 25 mm, 50 mm, 150 mm, and 300 mm. At a rainfall level of 10 mm, the simulation showed that certain parts of the community begin to experience localized waterlogging. This is primarily due to the reduced water-carrying capacity of certain small creeks and drains which occurs without the implementation of any diversion or augmentation measures. As a result, the water exceeds its capacity and has a detrimental effect on nearby regions, particularly those with inadequate drainage infrastructure. The vulnerability of the drainage system has been exposed, although the consequences are insignificant.

The situation begins to deteriorate when the amount of precipitation approaches 50 mm. At this level, the hamlet experiences more significant and impactful water flows, resulting in the breakdown of the drainage system over a wide area. This exacerbates the problem of internal waterlogging and increases the area over which the water is distributed, affecting a larger region. Under these circumstances, the village's infrastructure is highly vulnerable, especially the structures and facilities located in lower-elevation areas. At the same time, most of the villagers are also exposed to a higher probability of their well-being being endangered and experiencing damage to their property.

At its worst, the town experienced more than 150 mm of rainfall, which results in the flooding of the entire area and significant damage to structures. The villagers not only face a serious threat to their well-being but also suffer significant damage to their property. In such conditions, the rapid and efficient execution of emergency evacuation and rescue operations becomes critical.

Examining the simulations of different water level scenarios (Figure 13), it becomes clear that flood disasters occur primarily due to the inadequate capacity of the village's central drainage system to handle the total volume of water during such events. The external flooding resulting from the overflow of nearby rivers exacerbates the flooding situation of the village. The convergence of internal and external flooding results in a comprehensive disaster that amplifies the complexity and devastating impact of flooding.

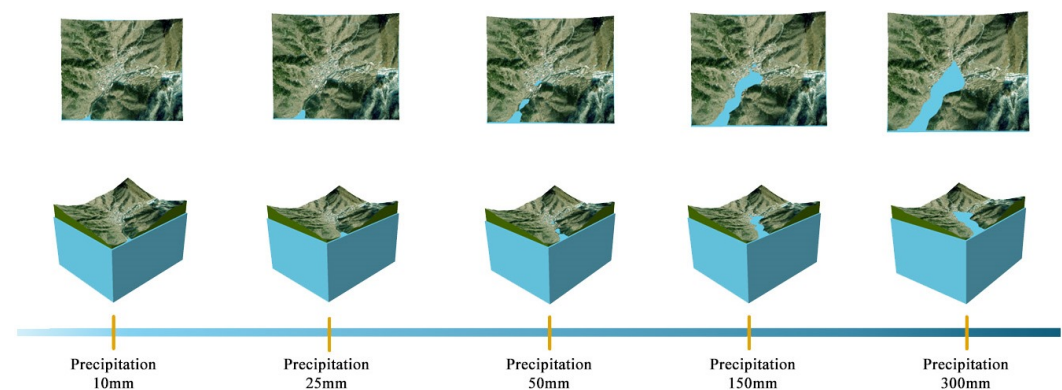


Figure 13. Flood inundation area analysis result.

To effectively address the complex flood hazard, the village of Stream Gully needs to implement a number of pragmatic measures. These include improving the drainage system in the central region, widening the current drainage ditches, increasing the number of drainage pipes, and constructing new drainage infrastructure such as cisterns or drainage pumping stations.

These techniques can improve the ability of villages to efficiently regulate the internal flow of water in response to significant amounts of rainfall.

Following the research, this paper proposes an alternative approach to surface runoff management. This involves improving surface runoff control by implementing a centralized flood control and diversion area. A localized water conveyance and diversion area will also be created to relieve the local drainage system. In addition, a flood buffer zone will be created to minimize the risk of flooding to the village.

2.6. Research Methodology and Innovation

2.6.1. Principles of Automatic Building Extraction

The Faster Region-Based Convolutional Neural Network (Faster R-CNN) is a deep learning model explicitly designed for target detection [33]. In the first stage, features are extracted from the input image using a convolutional neural network (CNN). This stage effectively captures the essential visual information present in the image. At the same time, the model incorporates a novel element called the Region Proposal Network (RPN), which quickly and effectively generates potential candidate regions. In this context, these regions in the image can contain a target, specifically, a building. Each proposed region is further examined to determine whether it contains a desired target and is then categorized. The Faster R-CNN algorithm refines the bounding box coordinates of these regions to obtain a more accurate coverage of the target object. During this process, image segments representing structures are detected and cropped from the original image in anticipation of further processing.

PolygonRNN is a model that uses a recurrent neural network (RNN) to accurately identify and represent the exact outlines of objects in an image. (This concept is illustrated

in Figure 14). PolygonRNN differs from traditional pixel-based image segmentation techniques in that it generates a sequence of vertices to create a polygonal outline of an object. This method is very effective when working with objects that have well-defined geometric characteristics, such as buildings. The model gradually outlines the structure, creating a polygon that accurately represents the shape of the building.

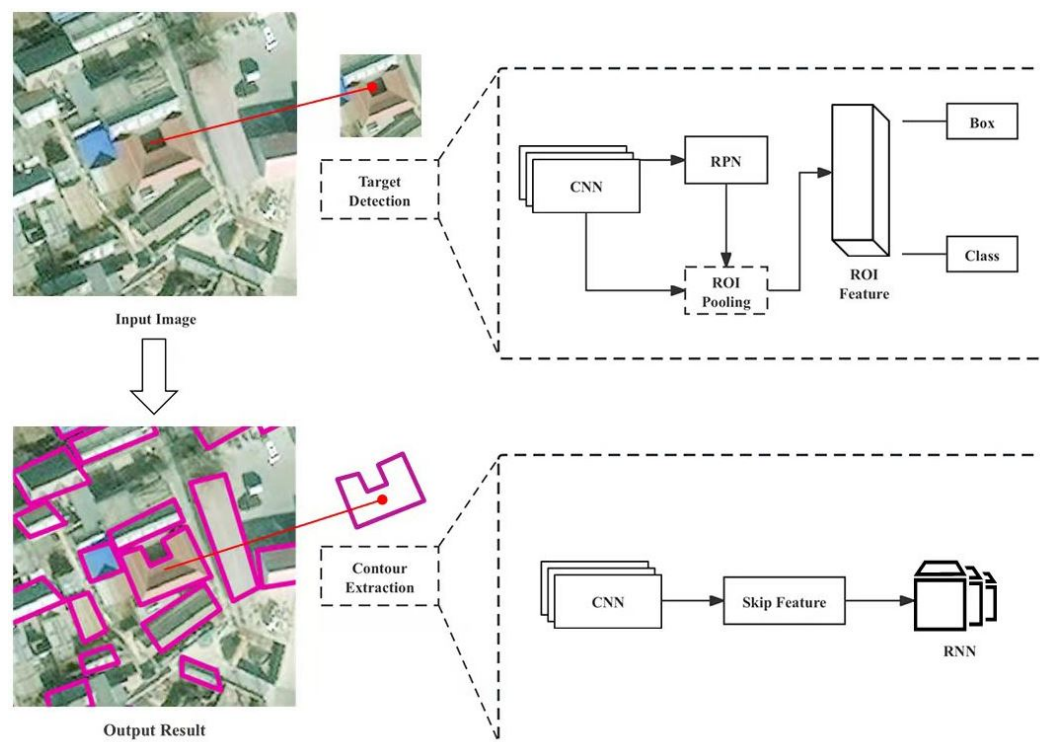


Figure 14. Schematic diagram of PolygonRNN-based building extraction.

2.6.2. Rationale of the Sponge City Construction Methodology for Village Adaptation

The term ‘sponge city’ was first used in 2014 and is widely used to address urban surface water flooding and other related challenges in urban water management [19]. At present, China is undergoing a period of rapid urbanization. In order to address the above issues, several cities have already implemented long-term water management strategies [34] and have water management capabilities suitable for the local environment [35]. China has implemented sponge cities, which have produced specific results [36]. However, the city’s primary focus is on the countryside, which is rarely used as a subject of experimentation. In conjunction with China’s specific circumstances, certain villages have elements of urbanization. However, the infrastructure of the region still needs to be completed due to insufficient local focus.

As a result, when faced with natural disasters, the local community suffers substantial economic losses, which significantly hinders the progress of urbanization. Therefore, in the process of urbanization, it is imperative to promote the widespread understanding and dissemination of information and culture, focusing on the principles of the sponge city and sponge village [37]. Consistent improvement and refinement of local infrastructure are increasingly important.

Figure 15 illustrates the exact scheme. Jiangou village has created an effective water management system by constructing an artificial diversion lake and implementing water management infrastructure such as artificial wetlands, urban storm water pipelines, and sunken green spaces that fully utilize local topography and land resources. The system is partially underground, with additional drainage pipes and diversion lines to increase underground infiltration capacity and effectively mitigate the risk of flooding. In addition, the implementation of a cistern, along with the installation of appropriate pumping

and drainage systems, facilitates water circulation between the artificial lake, the rice fields, and the cistern. This effectively increases the efficiency of rainwater harvesting and provides a comprehensive solution for water resource management in Jiangou village.

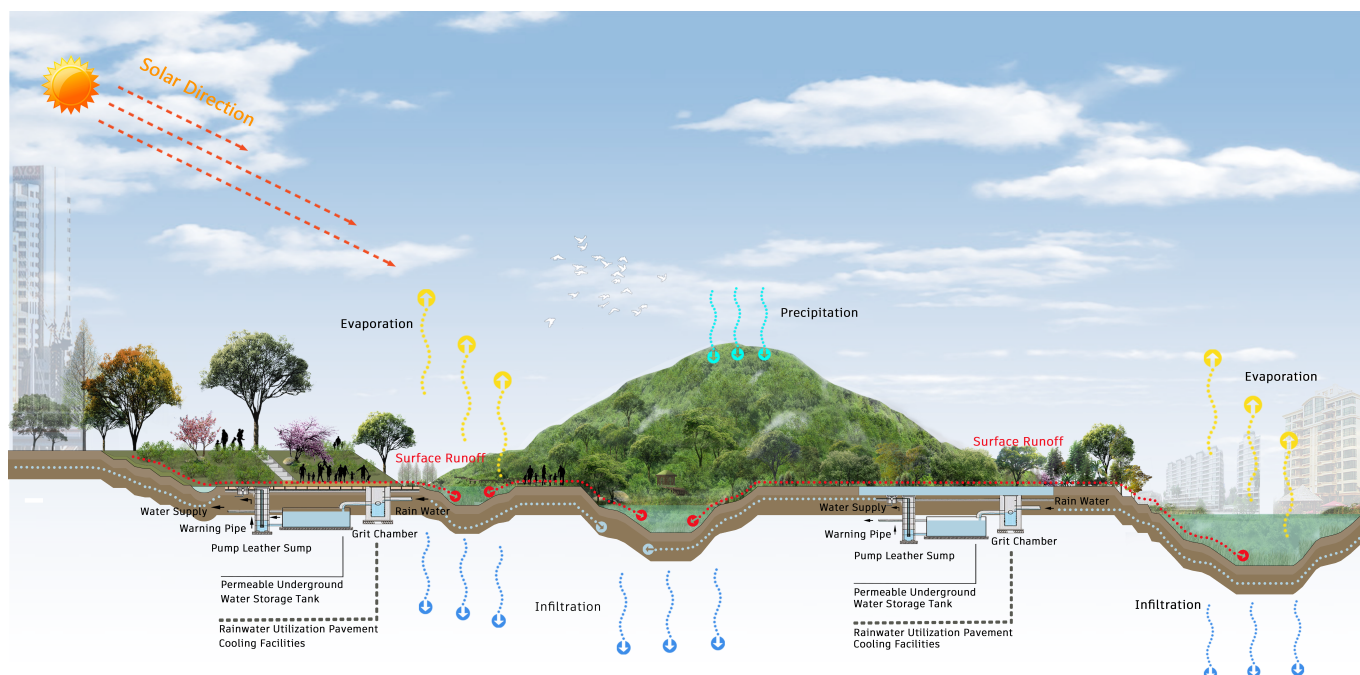


Figure 15. Principles of the SPCC approach for village adaptation.

3. Result and Discussion

3.1. Flood Disaster Risk Intelligent Management Program

3.1.1. Establishment of Small Artificial Lake

Since lakes are inevitably related to regional water storage capacity, and a reduction in the area of regional lakes increases the frequency of flooding [38], in order to improve the effectiveness of integrated water management in villages, it is recommended to construct artificial lakes. This will increase the village's water storage and impoundment capacity and enhance the regional flood management capacity of Jiangou village. It will also improve the ecological environment in the surrounding areas, as lakes play a crucial role in regional water storage and flood risk reduction. Our focus in designing the lakes and buffer zones was to prioritize the preservation and enrichment of biodiversity. For example, the deliberate selection of plants around the lakes and the creation of artificial wetlands were designed to attract native wildlife species, thereby improving the resilience and stability of the ecosystem. The development of artificial lakes serves multiple purposes, including flood control and rainwater storage to replenish the village during the dry season, thus achieving multiple use of water resources.

The study combined the topography of Jiangou village and the distribution of buildings (Figure 16), and the blue area in the figure was selected as the artificial lake area. Through the construction of small flood diversion lakes and the establishment of local terrain elevation buffer areas, the flood disaster problems facing Jiangou village are solved, and local natural resources are fully used to realize the sustainable development of the ecological environment.

According to the disaster situation during the heavy rainfall and flooding in Jiangou village, the water level of the river rose sharply, exceeding the warning level by more than 1.5 m, resulting in the flooding of the river. The dams in some sections of the river were washed out, and the water level of the river near Jiangou village even rose more than 4 m on

31 July, when the rainfall was heaviest, exceeding the warning level by 2 m. In Section 2.4.2, we calculated the difference in the area of the water body before and after the heavy rain and flooding, and combined the water level rise data and the rainfall data to calculate the flood flow and the capacity of the artificial diversion lake by the following steps.

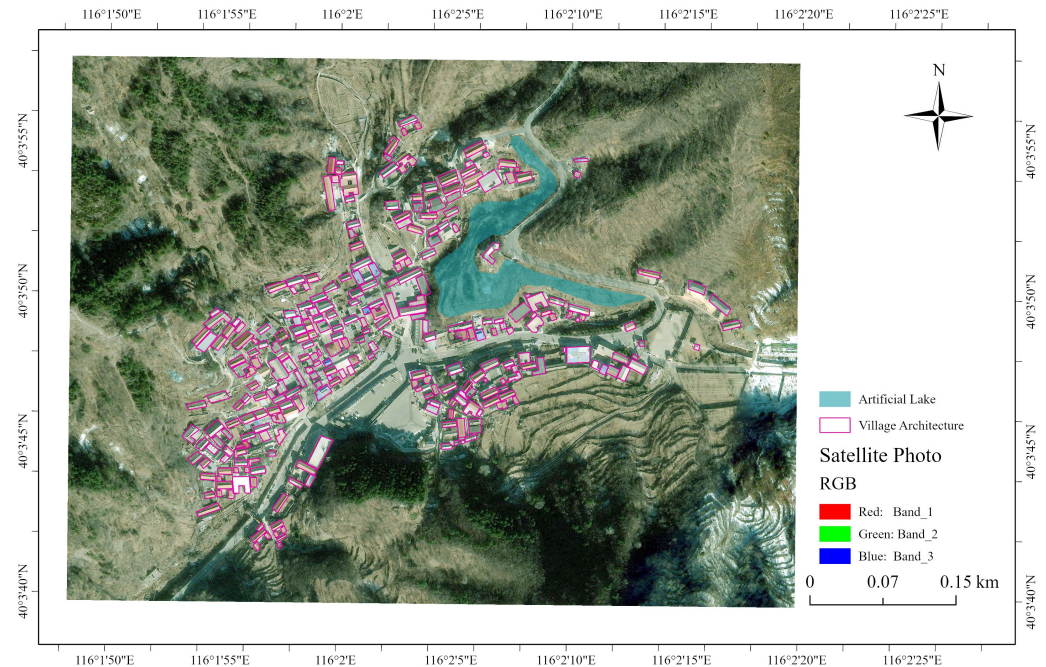


Figure 16. Artificial lakes plan.

(1) Calculate the flood flow [39,40].

The peak flow (annual exceedance probability flow) Q for different return periods of 20, 33, 50, and 100 years can be calculated using flood frequency equations (regional regression equations for frequency curve quantiles) [41], statistical flood analysis (statistical frequency-based runoff calculations for ‘hydrologically’ similar watersheds) [42], or flood frequency analysis (frequency function fitted to measured data) [43]. We used the following equation for the calculation:

$$Q = A * R, \quad (2)$$

where Q is the flood flow (m^3/s), A is the watershed area (m^2), and R is the precipitation (m/s).

The assumption that the maximum daily precipitation is about 200 mm, which is converted to an amount of about 2.31×10^{-6} per second, combined with the data on the area of the flooded body of water obtains a flood flow rate of about $9.897 \text{ (m}^3/\text{s)}$.

(2) Calculate the capacity of an artificial diversion lake [44,45].

Assuming that the design treatment time of the diversion lagoon is about 30 min (1800 s), the capacity of the diversion lagoon V can be calculated by the following equation:

$$V = Q * t, \quad (3)$$

where t is the time in seconds. The calculation gives the capacity of the artificial diversion lake as about $17,814.6 \text{ m}^3$. According to the field situation, we delineated the area of the scope of the diversion lake as about 8300 m^2 , and the projected depth of the artificial lake can be calculated by the following equation:

$$d = V / A_{\text{lake}}, \quad (4)$$

The depth of the artificial diversion lake was calculated to be about 2.15 m. These data can be used as a reference for the design and construction of the artificial diversion lake to

help Jiangou village effectively respond to possible future flooding. This approach not only scientifically and effectively addresses the challenges posed by extreme weather, but also creates a more liveable and environmentally friendly environment for the village.

3.1.2. Principles of Artificial Lake Construction

In developing the marginal flood buffer approach for Jiangou village, we took into account the basic principles of SPCC. This comprehensive water management strategy aims to reduce urban flooding by effectively managing rainfall through natural and artificial methods. We made creative modifications to adapt it to the specific needs of the rural area. When analyzing Jiangou village, we considered its rural setting, topography, and financial budget to successfully reduce flood risk within the constraints of local economic conditions.

By creating artificial diversion lakes, as shown in Figure 17, this study eliminates expensive components of the conventional SPCC approach, such as grass-lined canals and underground reservoirs. Although these services are sufficient in urban areas, they can be an unnecessary economic burden in rural areas. Instead, rice fields and artificial wetlands are included as components of the buffer zone. This part is designed to strengthen the water holding capacity of the area and preserve the ecology, thereby increasing functional diversity and improving resilience to unforeseen calamities. This is enhanced by modifying the arrangement of drainage ditches and strengthening existing water management infrastructure, such as watercourses and ditches, to increase drainage capacity and optimize flood control effectiveness during severe weather conditions.

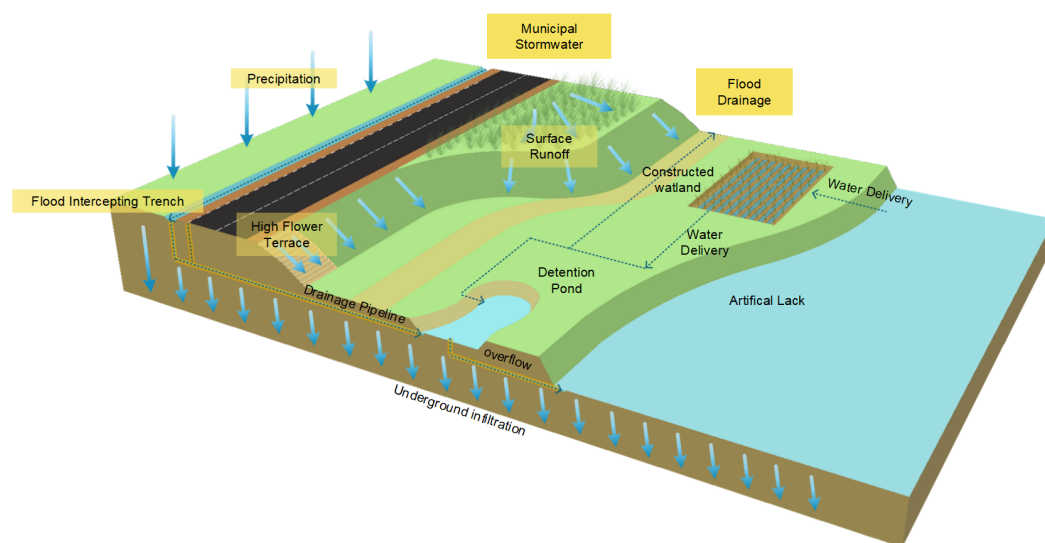


Figure 17. SPCC process control methodology for rural adaptation.

The implementation of the marginal flood buffer strategy in Jiangou village exemplifies a novel perspective on addressing flooding challenges in rural areas. The project considers both financial and environmental sustainability, and aims to improve the long-term efficiency of the water cycle and water use in Jiangou village while enhancing the sustainability of the local ecosystem.

3.1.3. Buffer Area Creation

This measure is implemented to mitigate the effects of flooding caused by intense rainfall, mainly to avoid the occurrence of water accumulation due to exceeding the capacity of artificial reservoirs. A novel approach to the management of the water body is implemented, which involves the creation of a buffer zone with a specific gradient around the lake. The approach was designed with two primary elements: a buffer zone with a slope of 3° and a range of 5 m and a buffer zone with a slope of 5° and a range of 10 m (Figure 18).

This design ensures optimal protection of village residents and structures even during significant flooding.

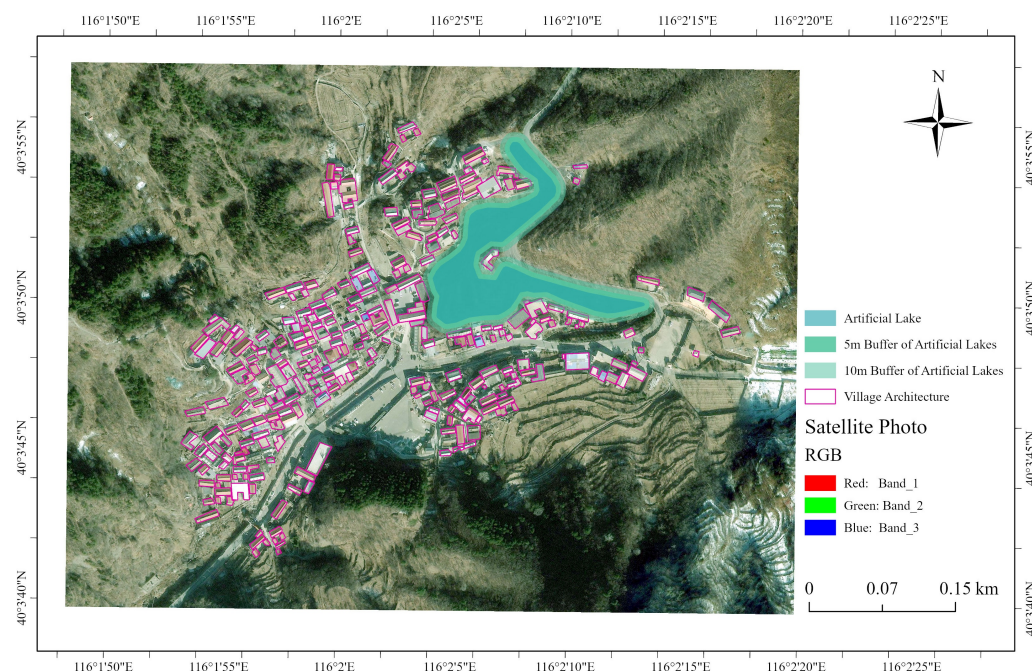


Figure 18. Artificial lake buffer establishment.

Installing buffers with varying degrees of slope provides the advantage of efficiently managing the rapid rise of the lake water level, thereby reducing the occurrence of backwater in the lake. During heavy rainfall, the lake level rises rapidly, and the slope buffer can act as a temporary reservoir for excess water. The 5 m and 10 m buffer zones are designed to accommodate different levels of rainfall intensity, ensuring that the village's water system can adequately handle different types of extreme weather.

In addition, the various slopes are designed to accommodate water movement patterns and erosion control requirements. The gradual 3° slope (with a range of 5 m) is appropriate for typical rainfall situations as it slows water movement and prevents soil erosion while allowing adequate water drainage. The 5° slope with a 10 m range is used in heavy rainfall and crisis situations to accelerate the flow of excess water and increase the effectiveness of drainage.

At the same time, these buffer zones ensure ecological preservation and implement landscape architecture. The creation of buffer zones mitigates flooding, enhances biodiversity, provides recreational opportunities for local residents, and promotes ecological balance. The concept of combining functionality and environmental sustainability in this design exemplifies the current trend of integrating contemporary water conservation initiatives with ecological preservation.

3.2. Discussion

This study is innovative in its methods and measures, but there are some limitations in data accuracy and timeliness as it mainly relied on satellite remote sensing data for rainfall analysis, which may affect the accuracy and timeliness of data. In addition, there is a lack of research on the simulation and prediction of flood dynamics [46]. In order to ensure the effectiveness and safety of flood management strategies, simulation techniques were used to predict the flood diversion area under extreme weather conditions to assess the responsiveness of the flood diversion area in the face of these extremes, and to provide a more accurate estimate of the value of flood risk in the flood diversion area. While there is a lack of more specialized assessment methods and standards in hydrology for

the design of artificial diversion lakes and the assessment of storage capacity, future work should introduce a standard assessment simulation system that will help us to assess the pre-discharge of reservoir storage based on forecasts [47,48] to improve the scientific and practical accuracy of the methodology.

In conclusion, this study still needs to be further improved in terms of data accuracy, simulation depth, and system evaluation, and it still needs rich, specialized theoretical knowledge and more accurate experiments to support the study in the future so as to develop more effective and practical flood management strategies for rural areas by combining multiple disciplines.

4. Conclusions

In this study, a comprehensive analysis of multiple methods was used to propose a village-adapted response to heavy rain flooding in response to the flooding in Jiangou village in late July 2023. First, through field exploration and data collection, a comprehensive topographic and hydrological characterization, including contour analysis, slope direction analysis, and slope gradient analysis, was conducted using high-resolution DEM and remote sensing image data to understand the topographic features and potential flood convergence areas of Jiangou village. Combined with GSDMap and CHIRPS meteorological data, the precipitation before and after the disaster was analyzed, and the results showed that the precipitation was highest on 30–31 July, which is consistent with the actual situation. Based on the Sentinel-2 data, the flood inundation area was extracted using the MNDWI and OTSU thresholding methods, and the quantitative analysis showed the change of the water body during the flood period, which increased by about 4.24 km² during the disaster. To determine the coverage and distribution density of buildings, a combination of Faster R-CNN and PolygonRNN was used for model construction to identify and extract the buildings in the area of Jiangou village. And, based on the above analysis, using the SPCC principle as a reference, a sponge village flood response method is proposed, in which the specific response measures include the establishment of artificial diversion lakes and local terrain buffer zones, the adoption of a modernized and upgraded drainage system, the widening of drainage ditches, the extension of drainage pipes, and the construction of water storage tanks and drainage pumping stations in order to improve the drainage capacity and flood control efficiency, increase the village's water storage and drainage capacity, and mitigate the effects of flooding.

From the contents and results analyzed in the study, it is clear that this method is theoretically sound. However, since our research field is mainly in GIS and RS, hydrological and hydraulic analyses are obviously beyond the scope of the research field; therefore, in our future research, we will seek the help of experts in these fields to conduct further analysis, analyze the adequacy of the present methodology from a quantitative point of view, and combine these analyses with existing contents to develop more effective flood management strategies for villages.

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