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# The Value of Traditional Ecological Knowledge in Stormwater Management: A Case Study of a Traditional Village

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**Abstract:** In recent years, floods have occurred frequently in urban and rural areas around the world, causing heavy casualties and property damage. In contrast, some traditional Chinese villages have never flooded. It is hypothesized that these villages, because of their long-term adaptations to their environment, hold necessary ecological knowledge regarding stormwater management so that damaging flooding can be avoided. Previous studies on the traditional ecological knowledge regarding stormwater management in traditional Chinese villages are mostly qualitative studies, and these fail in their evaluation of the functional performance of stormwater management facilities and measures. Therefore, we use the Storm Water Management Model (SWMM) in our quantitative evaluation of stormwater management in Zhuge, a traditional Chinese village, so as to rationally analyze the traditional ecological knowledge regarding stormwater management in traditional Chinese villages. In order to analyze the functions and efficiency of stormwater management facilities such as ponds, canals, and permeable pavement in Zhuge Village, this study sets out four scenarios: the No Pond Scenario (NO-PO), the No Canal Scenario (NO-CO), the No Permeable Pavement Scenario (NO-PP), and the actual Current Scenario (CS). The SWMM is used to simulate and quantitatively analyze the stormwater hydrological processes of the four scenarios in different rainfall return periods. The following conclusions emerged from our evaluation of the approaches used in Zhuge Village: (1) The rainwater regulation system composed of ponds, canals, and permeable pavement can play a dual role in alleviating rainstorm disasters and fully storing rainwater, achieving the flexible allocation of rainwater resources. It can effectively alleviate the problem of uneven time and space of local rainfall in shallow, hilly areas, reflecting the traditional ecological wisdom of residents in adapting to the local natural environment. (2) As a rainwater regulation device, ponds are very effective in storing water and mitigating periods of intense runoff. (3) The main function of canals is to rapidly drain water and balance rainwater resources. (4) The main function of permeable pavement is to increase rainwater infiltration and reduce the peak runoff and runoff. (5) The use of the SWMM proved effective in both quantifying the results as well as elucidating stormwater management strategies.

**Keywords:** traditional ecological knowledge; stormwater management; SWMM; traditional village; Zhuge village; pond

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## 1. Introduction

The intensification of global climate change and rapid urbanization have led to significant changes in the hydrological processes associated with human settlements [1,2]. The increased frequency of high-intensity rainstorm events has increased the frequency and intensity of global flood disasters [3]. Both urban and non-urban areas in various countries have increasingly serious flood problems [1,3,4]. Taking China as an example, flood disasters cause huge losses every year, such as the "7.20" extremely heavy rainstorm in Zhengzhou, China, 20 July 2021 [5], and the continuous heavy rainstorm in Beijing in the summer of 2023, which caused heavy casualties and property losses [6].

Some traditional Chinese villages provide excellent examples where flooding is rare or non-existent. These include Zhuge Village in Zhejiang Province, where there is no record of floods in its 700-year written history. The absence of flooding for centuries suggests that members of these villages have accumulated the traditional ecological knowledge necessary to manage their environments over time and space to avoid flooding [7]. This "traditional ecological knowledge" is "a cumulative body of knowledge, practice, and belief, evolving by adaptive processes and handed down through generations by cultural transmission, about the relationship of living beings (including humans) with one another and with their environment." [8]. It has strong characteristics of environmental adaptability and is the crystallization of practical wisdom for many generations [9]. Traditional ecological knowledge is also a practical tool that helps local people to adapt to climate risks and promotes sustainable resource management in their communities [10]. It thus has value and significance beyond the specific time and the country [11] and can provide guidance for research, planning, and construction regarding urban and rural development [12]. Unfortunately, many such traditional Chinese villages have been damaged by unreasonable construction and renovation in recent years, which has disrupted the harmonious relationship between humans and nature and has also begun to experience flood disasters [13]. Therefore, it is necessary to explore, analyze, and inherit the traditional ecological knowledge regarding rainstorm management in these traditional villages so as to provide references for correcting the current unreasonable urbanization construction mode.

Because of this, many scholars have paid attention to the traditional ecological knowledge related to rainstorm management in traditional villages in China. Liu et al. explored the relationship between traditional Chinese settlement site selection and flood prevention [7]. Yang et al. argued that "Water Layout" is a key factor in the creation, inheritance, and development of traditional villages [14]. Ou et al. stated that the water system spatial pattern of traditional villages determines the spatial pattern of villages [15]. Some scholars have also studied the rainwater organization system in the Old Town of Lijiang, suggesting that it reflects the idea of "harmony between man and nature" [11]. Zhou et al. found that in the western suburbs of Beijing, all rivers and lakes are continuously connected, forming a complex water conservancy system that integrates "diversion-storage-discharge-separation". This emphasizes the systematic spatial structure and is a model of comprehensive stormwater management for both urban and suburban areas [16]. Feng shui is an important aspect of stormwater management in traditional Chinese villages [17]. Traditional Chinese villages often choose sites with good feng shui that are backed by mountains and facing water, pursuing the harmonious coexistence of "Heaven, Earth, and Humanity" [18]. Some studies also suggest that ponds are an essential form of infrastructure for utilizing and managing water resources formed during the long-term adaptation process of people to the natural environment in traditional settlements [19,20]. They have the functions of collecting rainwater, regulating water resources, and improving water quality [21]. Due to the differences in water resources in different regions of China, there are also different strategies for stormwater management. Overall, the northern region is relatively dry, and stormwater management is mainly aimed at collecting and storing water. The southern region has abundant rainfall, and rainwater treatment mainly focuses on flood prevention and water diversion [17]. Stormwater management in traditional Chinese villages typically adopts a combination of artificial and natural methods involving six aspects of hydrology: seepage, stagnation, storage, drainage, purification, and the utilization of rainwater [15].

Overall, previous studies on the traditional ecological knowledge regarding stormwater management in traditional Chinese villages have mainly focused on qualitative research, lacking scientific quantitative analysis methods [21]. The effectiveness and functional value of traditional stormwater management facilities and measures have not been clearly evaluated, which is one of the reasons why current urban and rural settlement construction managers recognize traditional ecological knowledge but cannot learn from it. This leads to the lack of a strong and reliable scientific basis in village construction and renovation.

The accurate simulation of rainstorm hydrological processes can provide integral support for stormwater management [21]. The simulation model is a powerful tool for the scientific and rational analysis of stormwater management. Therefore, many computer models have been developed to simulate rainfall and flood hydrological processes, such as RORB, MOUSE, WBNM, HEC-HMS, and SWMM [4]. At present, the most commonly used rainstorm management model is the SWMM [4]. This model is well suited to hydrological simulation and analysis [2,22]. The main aims of this study are to accurately simulate the rainstorm hydrological processes in a traditional village based on the application of the SWMM and accurately evaluate the efficiency and functional value of traditional rainwater management facilities and measures, so as to realize the rational analysis of traditional ecological knowledge regarding stormwater management and provide scientific evidence for the construction and renovation of traditional villages.

The traditional ecological knowledge regarding stormwater management in traditional Chinese villages has only been studied qualitatively in the past. Thus, establishing how to conduct quantitative analysis through the SWMM and how to evaluate the functions and efficiency of various stormwater management facilities in traditional villages is a crucial challenge. In addition, traditional Chinese villages mainly exist in rural areas, while the SWMM was used mostly in urban areas in the past. Whether this model is suitable for stormwater management research in traditional Chinese villages is also a question. Based on this, this paper mainly aims to answer the following three questions:

(1) What are the main aspects of the ecological knowledge regarding rainwater management in traditional villages, and how should we build a traditional village rainstorm management model using SWMM software version5.2?

(2) How can the functions and efficiency of various stormwater management facilities and measures in traditional villages be simulated and reflected by the SWMM?

(3) The SWMM has been used to simulate rainstorm hydrology in urban areas. What special efforts should be made when it is used to simulate rainstorm hydrology in traditional village in hilly areas?

## 2. Materials and Methods

### *2.1. Description of the Study Area*

#### 2.1.1. Study Area

The study area is located in Zhuge Village, 18 km west of Lanxi City, Jinhua City, Zhejiang Province, China, with an area of 51.9 hectares (Figure 1). This village was founded by Zhuge Dashi, the 27th generation descendant of Zhuge Liang, in the mid Yuan Dynasty of China, with a history spanning more than 700 years. There are more than 200 ancestral halls and residential buildings of the Ming and Qing dynasties that are still well preserved in Zhuge Village. Zhuge Village was listed as a national key cultural protection unit in 1996, is the first ancient village in China to be protected as a whole, and still retains a relatively complete original village spatial layout. This village is located in a subtropical monsoon humid climate zone with a mild climate. The average temperature over the course of the year is 17.9 °C, and the annual average relative humidity is 74%. The rainfall is abundant and unevenly distributed, with an average annual rainfall of 1458.3 mm. The rainfall from March to September is 1110.40 mm, accounting for 76.10% of the annual rainfall [23]. This research area has abundant groundwater resources, with the groundwater level only 1–2 m below ground level. The main soil is red loam, followed by yellow loam and paddy soil [23]. The overall terrain of this study area is high in the north and low in the south, with the highest point located in the north at an altitude of 91.1 m and the lowest point at the southeast corner at an altitude of 58.4 m. The average slope of the entire research area is 10.49%.

Zhuge Village is a typical traditional settlement located in the shallow, hilly areas of southern China. In these areas, rivers are generally scarce, and the village uses ponds as its main source of domestic water. The depressions in Zhuge Village have been shaped into ponds. Centered around these ponds, residential buildings gradually rise along the terrain, forming basin-shaped clusters. There are ponds in and around Zhuge Village (Figure 1). The internal ponds are mainly used for domestic use, while the surrounding ponds have the dual function of both domestic use and farmland irrigation.

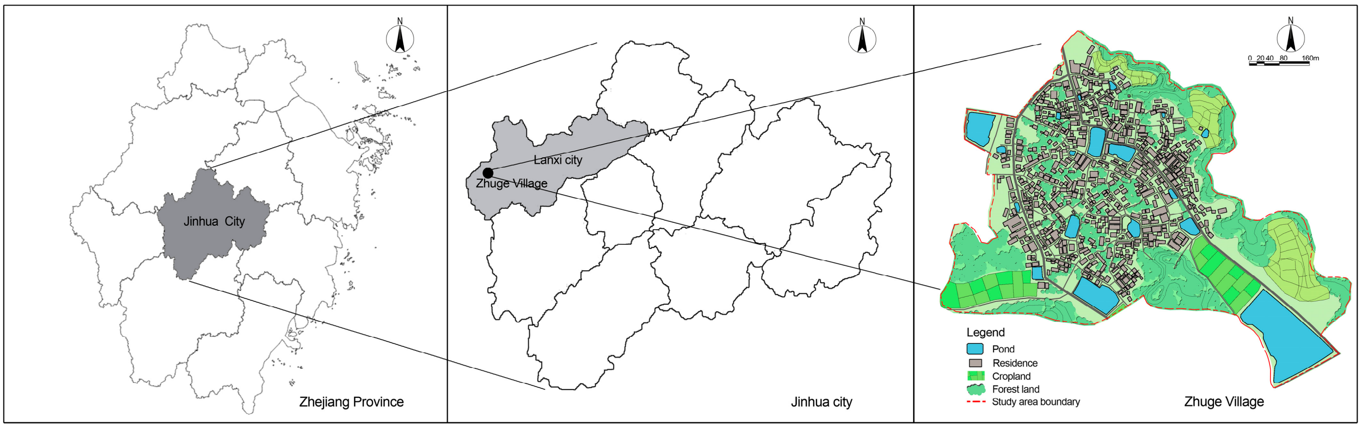


**Figure 1.** Site map of the study area. The study area is located in Zhuge Village, Lanxi City, Jinhua City, Zhejiang Province, China.

2.1.2. Stormwater Management Facilities and Measures in the Study Area

In the process of adapting to nature, Zhuge Village has formed a rainwater regulation system with great ecological wisdom, which mainly consists of elements such as ponds, canals, permeable pavement, etc. (see Figure 2).

(1) Ponds are the key element in stormwater management in Zhuge Village, with a dual function of water storage and flood discharge. There are 19 ponds in Zhuge Village (see Figure 2 and Table 1), which are evenly distributed around low-lying areas of the village. Rainwater around each pond will flow into the pond, forming a catchment area within a certain range around each pond.

**Table 1.** Attributes (area and depth) of the 19 ponds in Zhuge Village.

| Pond Label | Pond Area ($m^2$) | Pond Depth (m) | Pond Label | Pond Area ($m^2$) | Pond Depth (m) |
|---|---|---|---|---|---|
| 1 | 460.9 | 2.5 | 11 | 1923.2 | 2.7 |
| 2 | 200.7 | 1.9 | 12 | 1267.0 | 2.5 |
| 3 | 202.1 | 2 | 13 | 472.7 | 2 |
| 4 | 3396.3 | 3 | 14 | 383.6 | 2.1 |
| 5 | 351.9 | 2 | 15 | 2040.0 | 2.5 |
| 6 | 2646.4 | 2.9 | 16 | 1157.9 | 2.4 |
| 7 | 237.4 | 2.3 | 17 | 6199.1 | 3.1 |
| 8 | 63.4 | 1.9 | 18 | 27,397.1 | 3.5 |
| 9 | 384.3 | 2.6 | 19 | 5617.0 | 3 |
| 10 | 496.5 | 2.5 | | | |

(2) Water canals are the main water transport facilities, generally arranged in accordance with the terrain or along streets, and have the function of connecting ponds, water diversion, and drainage. There are open and hidden canals in the village, and open canals are more common, making the collection and drainage of water in the village easier. The width of the canals in Zhuge Village ranges from 0.3 m to 1.8 m, and the depth of the canals ranges from 0.3 m to 1.5 m. Generally, the canals located in main streets are wider and deeper, while those in alleys are narrower and shallower.

(3) Permeable pavement. The sites and roads within Zhuge Village are mostly paved with permeable materials. The wider roads in the village are mostly paved with regular bluestone slabs, which are smooth and can evacuate rainwater quickly; narrow roads and

sites are mostly paved with pebbles or gravel, which is conducive to rainwater infiltration and can slow down rainwater runoff [24].

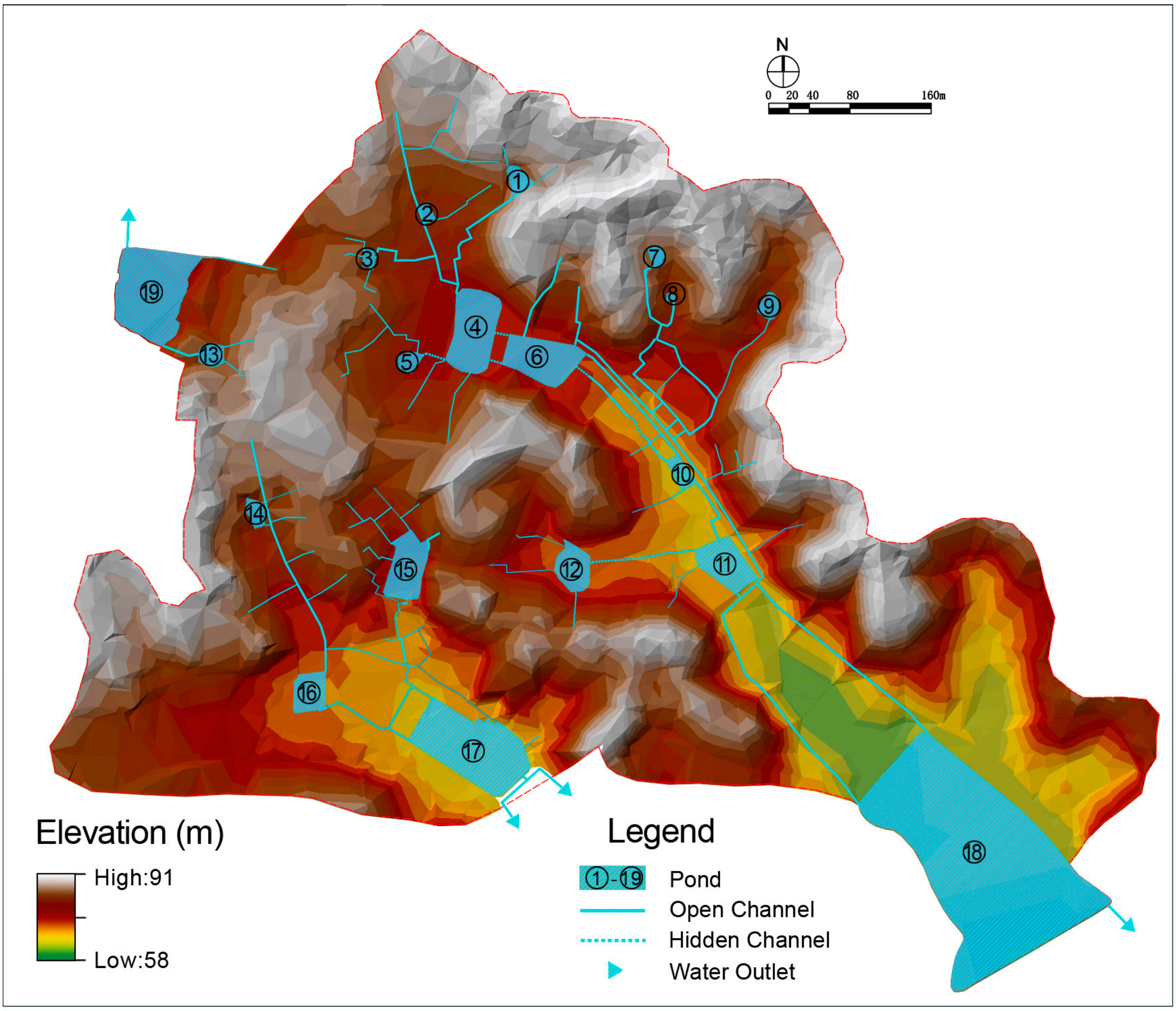


**Figure 2.** Distribution of stormwater management facilities in Zhuge Village.

The villagers of Zhuge Village treat a rainstorm not only as a disaster but also as a resource. In their stormwater management, Zhuge Village's occupants pay attention to rapid rainwater drainage to avoid flood disasters and also attach importance to collecting and storing rainwater for daily use and irrigation. Zhuge Village has achieved the objectives of orderly water collection, rapid drainage, and sufficient water storage through facilities such as ponds, canals, permeable paving, and related measures in order to achieve the goal of seeking advantages and avoiding disadvantages.

### 2.2. Data Used

The SWMM was used to simulate and quantify the rainstorm hydrological process in Zhuge Village. The following data are needed to construct a SWMM: precipitation data, sub-catchment data, infiltration data, conduit data, junction data, pond data, topographic elevation data, land use data, etc. The sources of these data are shown in Table 2.

**Table 2.** Data sources for hydrological simulation.

| Data Type | Specific Parameters | Data Source |
|---|---|---|
| Precipitation data | Precipitation intensity and time | Calculated according to the Lanxi rainstorm intensity formula: $i = \frac{3490.405(1+0.919\lg P)}{167(t+12.15)^{0.875}}$ where i is the storm intensity (mm/min); t is the storm duration (min); and P is the return period (year) |
| Sub-catchment data | Sub-catchment area and average slope | The sub-catchment area can be calculated automatically in SWMM software version5.2. The average slope of the sub-catchment area is calculated by GIS, according to the elevation data of Zhuge Village |
| | Characteristic width | Calculated based on the formula for characteristic width (W): $W = K\sqrt{A}$ where A is the catchment area, $m^2$; $0.2 < K < 5$ |
| | % imperv | According to the statistics of land use status |
| | N-Impervious, N-Pervious, Dstore-Impervious, Dstore-Pervious, and %Zero-Impervious | The initial value is set according to the relevant literature [25–28], and the final parameter values are determined by calibration |
| Infiltration data | Max. Infil. Rate, Min. Infil. Rate, Decay Constant, and Drying Time | The initial value is set according to the relevant literature [25,27,29–32], and the final parameter values are determined by calibration |
| Conduit data | Conduit length, shape, size, inlet offset, and outlet offset | Obtained through relevant information provided by the Zhuge Village Committee combined with on-site measurements |
| | Manning's roughness coefficient | The initial value is set according to the relevant literature [25,27,29–32], and the final parameter values are determined by calibration |
| Junction data | Invert elevation, max. depth, initial depth, and surcharge depth | Obtained through relevant information provided by the Zhuge Village Committee combined with on-site measurements |
| Pond data | Pond size And depth, and inlet and outlet Location | Obtained through relevant information provided by the Zhuge Village Committee combined with on-site measurements |
| Topographic data | Elevation topographic map | The Zhuge town government provided a 1:1000 CAD topographic map |
| Land use data | Land use type and area | On the basis of the land use map provided by the Zhuge town government, the land use data were obtained by combining the aerial map with the field survey |

## *2.3. Research Methods*

### 2.3.1. Establishment of the SWMM

In this study, the SWMM was used to simulate and analyze the rainstorm hydrological processes and the function of stormwater management facilities and measures in Zhuge Village.

#### Conceptualization of Regional Drainage Systems in the Research Area

The result of the conceptualization of the drainage system in the study area is shown in Figure 3. According to the terrain conditions, ponds' distribution, and water canals' convergence direction, the study area is divided into 31 sub-catchments (see Table 3). Sub-catchment boundaries in hilly areas in the study area are determined according to the location of the ridgelines, while sub-catchment boundaries in flat areas are mainly determined according to the direction of surface runoff convergence and the distribution of water canals [33]. In addition, there are 90 sections of conduits and 4 runoff outlets. In the SWMM, the pond is set as a storage unit. The pond inlet is connected to the upstream conduits, and orifice is set at the pond outlet. The pond outlet is generally located at the top of the pond, meaning that it is conducive to storing rainwater during a rainstorm, and when the pond is nearly full, it can be quickly drained through the outlet. The conduits are mainly open canals, and the depth and width of canals are set according to the actual survey and measurement values. The roads and sites mainly consist of permeable pavement, such as pebbles and gravel. In the SWMM, the scale of permeable pavement is mainly reflected by the proportion of impervious area in each sub-catchment area.

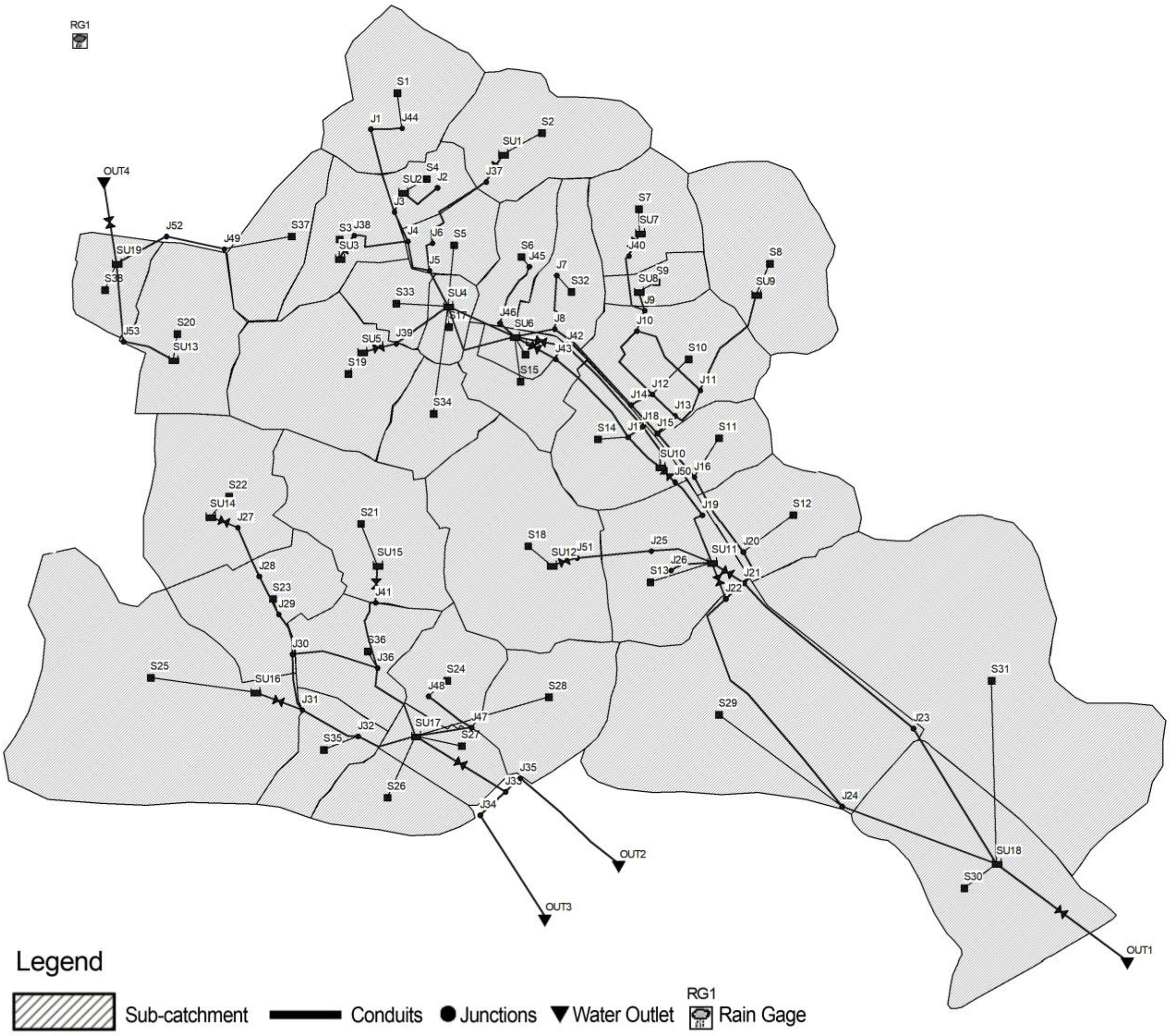


**Figure 3.** The SWMM model of the study area.

In this study, it was assumed that the rainfall in each sub-catchment area in the study area is evenly distributed, and the nonlinear reservoir model was used for surface runoff simulation [34], while in the flow routing process, the dynamic wave routing method was adopted [34].

Designed Rainfall

The precipitation is the key input variable of the SWMM [35]. In order to facilitate horizontal comparison, a rainfall hyetograph was used in this study. The rainstorm intensity was expressed by the Horner rainstorm intensity formula [36]. Since the rainstorm in China is dominated by a unimodal rainfall pattern, which is also easy to lead to floods, the Chicago rainfall pattern, characterized by unimodal process and symmetry, which is widely used in China [31,36–38], was used to reflect the distribution process of rainfall intensity on the time scale [39]. The Horner rainstorm intensity formula is as follows [36]:

$$i = \frac{A(1 + ClgP)}{167(t + b)^n} \quad (1)$$

where i is the storm intensity (mm/min); t is the storm duration (min); P is the return period (year); and A, C, b, and n are the constants, varying by city and region. In Lanxi City, A is 3490.405, b is 12.15, C is 0.919, and n is 0.875 [40].

**Table 3.** Basic information of each sub-catchment.

| Sub-Catchment | Area (ha) | Average Slope (%) | Imperviousness (%) | Sub-Catchment | Area (ha) | Average Slope (%) | Imperviousness (%) |
|---|---|---|---|---|---|---|---|
| S1 | 1.48 | 10.8 | 36.93 | S20 | 1.38 | 9.06 | 10.21 |
| S2 | 1.53 | 22.66 | 9.60 | S21 | 1.77 | 10.02 | 28.30 |
| S3 | 0.85 | 5.44 | 40.33 | S22 | 1.78 | 9.5 | 22.83 |
| S4 | 0.42 | 4.65 | 48.96 | S23 | 1.25 | 10.08 | 38.06 |
| S5 | 0.54 | 13.57 | 56.28 | S24 | 0.75 | 11.67 | 38.58 |
| S6 | 0.64 | 15.27 | 50.79 | S25 | 4.42 | 6.68 | 0.00 |
| S7 | 0.93 | 22.59 | 13.89 | S26 | 0.73 | 5.05 | 0.00 |
| S8 | 1.81 | 22.07 | 0.00 | S27 | 0.62 | 0 | 100.00 |
| S9 | 0.35 | 12.64 | 25.55 | S28 | 1.24 | 14 | 24.84 |
| S10 | 1.50 | 12.26 | 37.07 | S29 | 4.12 | 8.61 | 0.00 |
| S11 | 0.62 | 17.64 | 27.13 | S30 | 2.74 | 0 | 100.00 |
| S12 | 1.11 | 19.75 | 15.83 | S31 | 5.97 | 13.31 | 2.97 |
| S13 | 1.46 | 9.55 | 32.96 | S32 | 0.77 | 15.85 | 32.83 |
| S14 | 1.00 | 10.56 | 41.92 | S33 | 0.50 | 5.23 | 60.72 |
| S15 | 0.64 | 14.81 | 44.40 | S34 | 0.73 | 10.72 | 48.32 |
| S16 | 0.25 | 0 | 100.00 | S35 | 0.70 | 3.54 | 3.29 |
| S17 | 0.34 | 0 | 100.00 | S36 | 1.04 | 5.72 | 40.86 |
| S18 | 2.67 | 11.45 | 35.61 | S37 | 0.84 | 6.52 | 17.50 |
| S19 | 1.83 | 6.52 | 33.65 | S38 | 0.57 | 0 | 100.00 |

According to the rainstorm intensity formula of Lanxi City, the rainfall of rainstorms with return periods of 1a, 2a, 3a, 5a, 10a, 20a, and 50a was calculated, respectively, and the results were 35.14 mm, 44.86 mm, 50.55 mm, 57.71 mm, 77.15 mm, and 99.73 mm, respectively, without considering the spatial variation of precipitation. The Chicago rainfall hydrograph model [31] was adopted to set the precipitation time distribution, with the rain peak coefficient r at 0.3, the time interval at 1 min, and the rainfall duration at 2 h. The rainfall hydrograph curves of different rainfall return periods are shown in Figure 4.

Model Parameter Settings and Calibration

The SWMM contains many parameters, which can be roughly divided into two categories: deterministic parameters (geometric parameters) and uncertain parameters (empirical parameters). Deterministic parameters have clear physical meanings and can be obtained directly through the relevant data or tools [25–28] (see Table 2). Uncertainty parameters cannot be directly measured or obtained through calculation and generally require parameter values to be determined through calibration.

Calibration generally requires two steps: (1) setting initial values for uncertain parameters; and (2) uncertain parameter calibration.

(1) Initial value setting of uncertainty parameters.

The uncertainty parameter values need to be initially set and then determined through calibration. The initial values of uncertainty parameters are set according to the parameter values recommended by the SWMM manual and the related literature [25,27,29–32], as shown in Table 4.

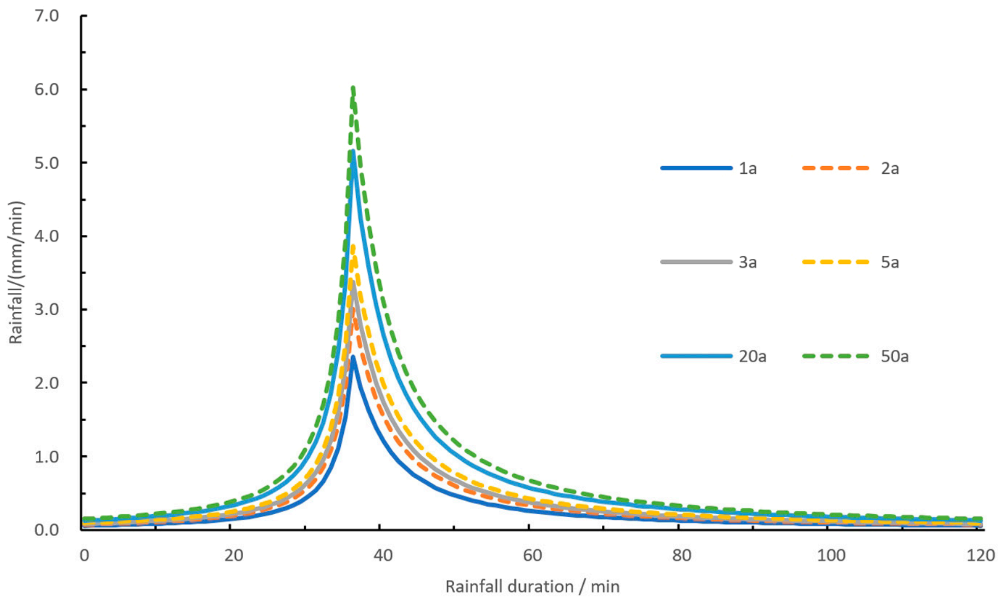


**Figure 4.** Rainfall hydrograph of different rainfall return periods in Lanxi City when the rainfall peak coefficient is 0.3. 1a refers to a rainstorm with a one-year return period; 2a refers to a rainstorm with a two-year return period; 3a refers to a rainstorm with a three-year return period; 5a denotes a rainstorm with a five-year return period; 20a represents a rainstorm with a 20-year return period; and 50a denotes a rainstorm with a 50-year return period.

**Table 4.** Initial values of uncertain parameters.

| Parameter | Initial Value |
|---|---|
| N-Impervious | 0.014 |
| N-Pervious | 0.3 |
| Dstore-Impervious | 1.5 |
| Dstore-Pervious | 5 or 8 |
| Max. Infil. Rate (mm/h) | 76.2 |
| Min. Infil. Rate (mm/h) | 3.81 |
| Decay constant (1/h) | 3 |
| Drying time (day) | 7 |
| N-Conduit | 0.015 |

(2) Uncertain parameter calibration.

Due to the lack of measurement data on runoff and rainfall in rural areas of China, many parameters required for the SWMM are difficult to calibrate using actual data. Therefore, the runoff coefficient method [41] was adopted in this study to calibrate the model parameters. Because the comprehensive runoff coefficient of the study area with a specific terrain and underlying surface was a relatively stable value, if the simulated value of the runoff coefficient calculated by the SWMM was close to the actual comprehensive runoff coefficient value, this indicated that the model was reasonable.

The calibration process was as follows: the comprehensive runoff coefficient of the study area was taken as the objective function, and the model parameters to be calibrated and their initial values were determined according to the SWMM manual and the related literature. The Chicago approach was applied to design a rainfall hyetograph with different return periods of 1a, 2a, and 3a, and the rainfall process of 2a was entered into the SWMM with set initial parameters. The Horton formula was used for infiltration, and the dynamic wave routing model was used for confluence [42]. The simulated runoff coefficient values were compared with the objective function, and we performed multiple iterations of calibration on the parameters. Then, the robustness of the calibrated model parameters were verified using rainfall processes with return periods of 1a and 3a. If both met the requirements of empirical values or comprehensive runoff coefficients, this indicated that the model was relatively reasonable.

The comprehensive runoff coefficient of the study area was calculated by using the weighted average method according to the runoff coefficient of different land use types and the proportion of the area in the study area [5]. According to the Standard for Design of Outdoor Wastewater Engineering (GB 50014-2021) [37] and the relevant literature [38], the runoff coefficient values for the main land use types in Zhuge Village were as follows: 0.9 for buildings or impermeable roads, 0.6 for large stone-paved roads or sites, 0.4 for gravel permeable roads or sites, 1 for water surfaces, and 0.2 for green spaces. Finally, the comprehensive runoff coefficient of the study area was about 0.405.

In the SWMM, multiple adjustments were made to the parameters for calibration, so that the simulated runoff coefficient was infinitely close to 0.405, and the "satisfactory solution" of the model parameters was obtained (see Table 5). The rainfall processes with two return periods, 1a and 3a, were then used to test the model. The impervious area ratio of the study area is 26.3%, meaning that it represents an area with the sparsest building density [37]. The simulated runoff coefficients for 1a and 3a were 0.302 and 0.446, respectively, consistent with the empirical values for the areas with the sparsest building density (Table 6). This indicates that the model has good stability and reasonable model parameters, which can be used for subsequent research. The validated parameter values are shown in Table 7.

**Table 5.** Parameter calibration process.

| | Initial Value | First Calibration | Second Calibration | Third Calibration | Fourth Calibration | Fifth Calibration |
|---|---|---|---|---|---|---|
| N-Impervious | 0.014 | 0.012 | 0.012 | 0.012 | 0.012 | 0.012 |
| N-Pervious | 0.3 | 0.25 | 0.25 | 0.15 | 0.15 | 0.15 |
| Dstore-Impervious | 1.5 | 1.3 | 1.3 | 1.00 | 1.00 | 1.00 |
| Dstore-Pervious | 5 | 3.8 | 3.8 | 2.50 | 2.50 | 2.50 |
| Max. Infil. Rate (mm/h) | 76.2 | 76.2 | 74 | 74.00 | 72 | 71.5 |
| Min. Infil. Rate (mm/h) | 3.81 | 3.81 | 3.81 | 5.00 | 5.00 | 5.00 |
| Decay constant (1/h) | 3 | 3 | 3.00 | 3.00 | 2.9 | 2.9 |
| Simulated runoff coefficient | 0.363 | 0.389 | 0.399 | 0.403 | 0.404 | 0.405 |
| Comprehensive runoff coefficient | 0.405 | 0.405 | 0.405 | 0.405 | 0.405 | 0.405 |

**Table 6.** Experience value of the comprehensive runoff coefficient [3,37].

| Area Situation | Comprehensive Runoff Coefficient |
|---|---|
| Areas with the densest buildings (impervious area rate $\geq$ 70%) | 0.60~0.80 |
| Areas with denser buildings (impervious area rate 30~70%) | 0.45~0.60 |
| Areas with sparse buildings (impervious area rate $\leq$ 30%) | 0.20~0.45 |

### 2.3.2. Scenario Design

In order to analyze the effects of different stormwater management facilities, such as ponds, canals, and permeable pavements, on runoff mitigation and rainwater utilization in Zhuge Village, an independent analysis of stormwater management elements is needed. Scenario analysis is a common method in related research based on the SWMM [43,44]. Based on the SWMM of the current situation (Current Scenario, CS, also referred to as the Control Situation) of Zhuge Village, three hypothetical scenarios were designed: the No Pond Scenario (No-PO), the No Canal Scenario (No-CO), and the No Permeable Pavement Scenario (No-PP).

**No-PO**: No-PO is based on the CS, in which the ponds are removed and replaced with ordinary nodes.

**Table 7.** The uncertain parameters' calibration results.

| Type | Parameter | Unit | Parameter Calibration Result |
|---|---|---|---|
| Sub-catchment parameters | N-Impervious | / | 0.012 |
| | N-Pervious | / | 0.15 |
| | Dstore-Impervious | mm | 1.00 |
| | Dstore-Pervious | mm | 2.50 |
| | Max. Infil. Rate (mm/h) | mm/h | 71.5 |
| | Min. Infil. Rate (mm/h) | mm/h | 5.00 |
| | Decay constant (1/h) | 1/h | 2.9 |
| | Drying time (day) | day | 7 |
| Conduit parameters | N-Conduit | / | 0.015 |

**No-CO**: No-CO is based on the CS. After removing the canals, surface runoff can be directly transmitted between sub-catchment areas, and the runoff from each sub-catchment area will eventually flow into nearby ponds with lower terrain.

**No-PP**: No-PP is also based on the CS, replacing the permeable pavement (road surface or site) in each sub-catchment area with impermeable pavement, thereby increasing the impermeability rate of each sub-catchment area.

CS, or the Control Situation, represents the situation in which all stormwater management facilities in Zhuge Village are complete. The three hypothetical scenarios (No-PO, No-CO, and No-PP), by comparison with the CS, represent the functional effects of ponds, canals, and permeable pavements, respectively, on stormwater management in Zhuge Village, as shown in Figure 5.

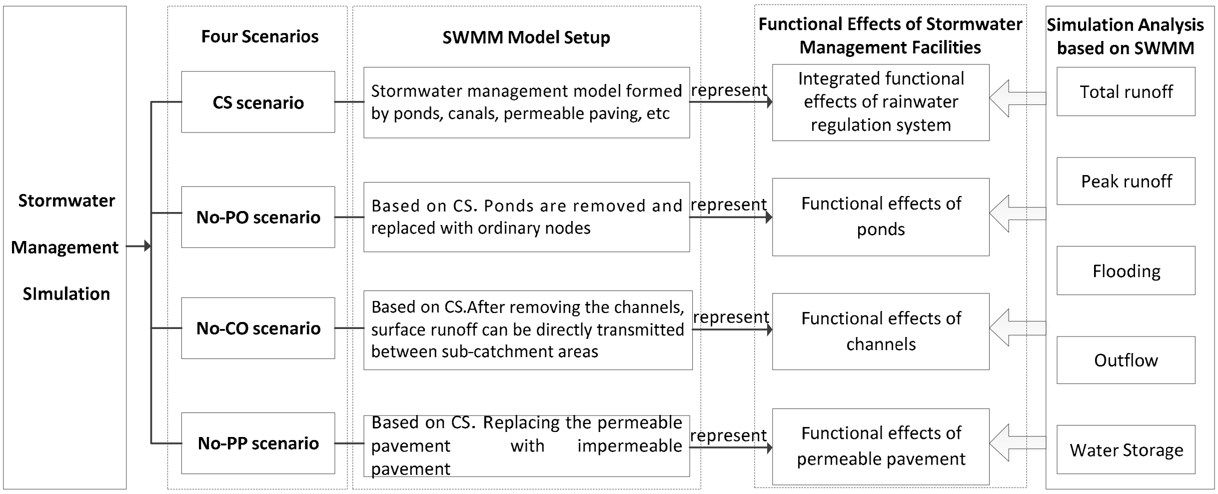


**Figure 5.** Simulation and analysis framework of stormwater management in different scenarios in Zhuge Village.

## 3. Results

In this paper, the total runoff, peak runoff, flooding, outflow, and storage of the four scenarios are compared and analyzed. The analysis results are as follows.

### *3.1. Total Runoff*

The simulation results of the total runoff of CS, No-PO, No-CO, and No-PP with different rainfall return periods are shown in Figure 6. The total runoff of the CS for the return periods of 2a, 5a, 20a, and 50a is 9568.8 $m^3$, 15,644.4 $m^3$, 25,275.6 $m^3$, and 31,747.8 $m^3$, respectively. From Figure 6, it can be seen that the total runoff of No-CO and No-PP is significantly higher than that of CS, while No-PO is basically equivalent to CS. It is interesting to note that the total runoff of No-PP is the largest for the 2a and 5a return periods, while the total runoff of No-CO is the largest for the 20a and 50a return periods.

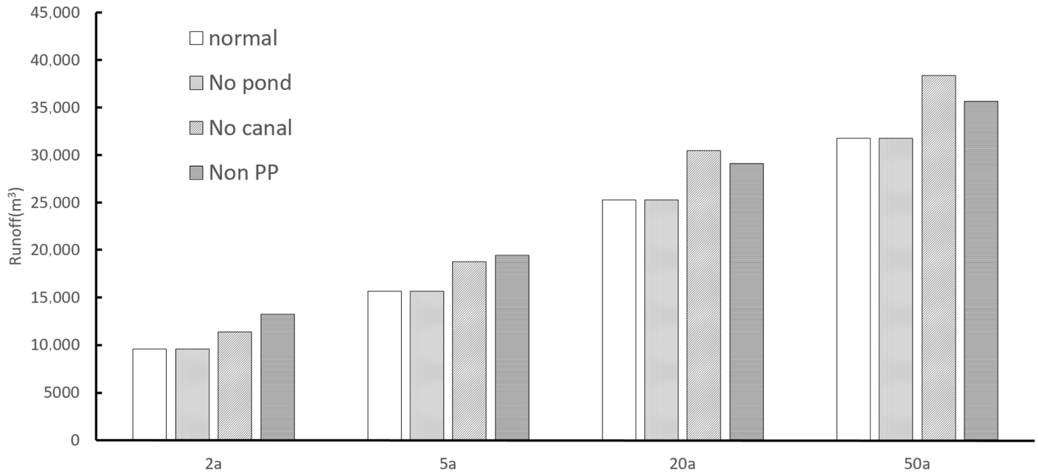


**Figure 6.** Comparison of the total runoff of four scenarios for different rainfall return periods: 2a refers to a 2-year return period; 5a refers to a 5-year return period; 20a refers to a 20-year return period; and 50a refers to a 50-year return period.

## 3.2. Peak Runoff

The peak runoff of CS, No-PO, No-CO, and No-PP for different rainfall return periods is shown in Figure 7. The peak runoff of No-PP and No-CO is significantly higher than that of CS, while No-PO is comparable to CS, indicating that permeable pavement and canals have a greater effect on reducing the peak runoff, while the effect of ponds is not significant.

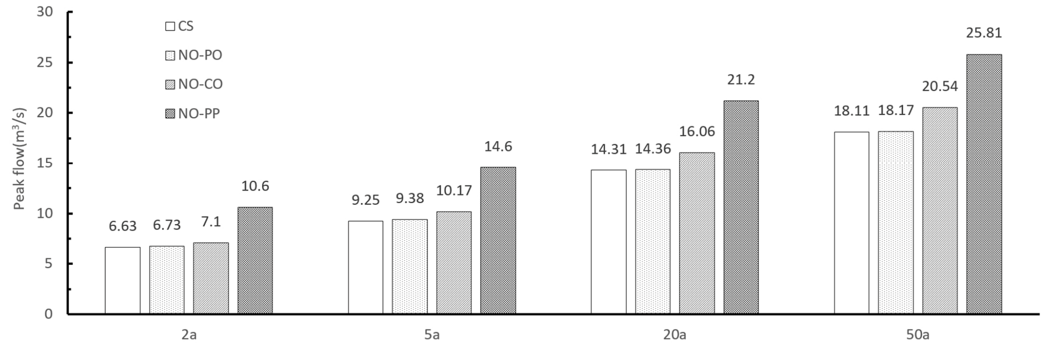


**Figure 7.** Comparison of the peak runoff of four scenarios for different rainfall return periods: 2a refers to a 2-year return period; 5a refers to a 5-year return period; 20a refers to a 20-year return period; and 50a refers to a 50-year return period.

## 3.3. Flooding

Flooding is the most direct indicator reflecting the situation regarding a rainstorm disaster in the village. As can be seen from the flood simulation results of different rainfall return periods (Figure 8), CS did not flood even in the rainstorm with a 50a return period. No-PO and No-CO showed obvious flood problems for the four rainfall return periods, and No-PP also began to flood at 50a. From the perspective of flooding time, flooding in No-PO started earlier, but the flooding time was shorter. Although the start time of flooding in No-CO is later than that in No-PO, the duration of flooding is longer. In terms of flood volume, the total flood volume of No-CO is the largest.

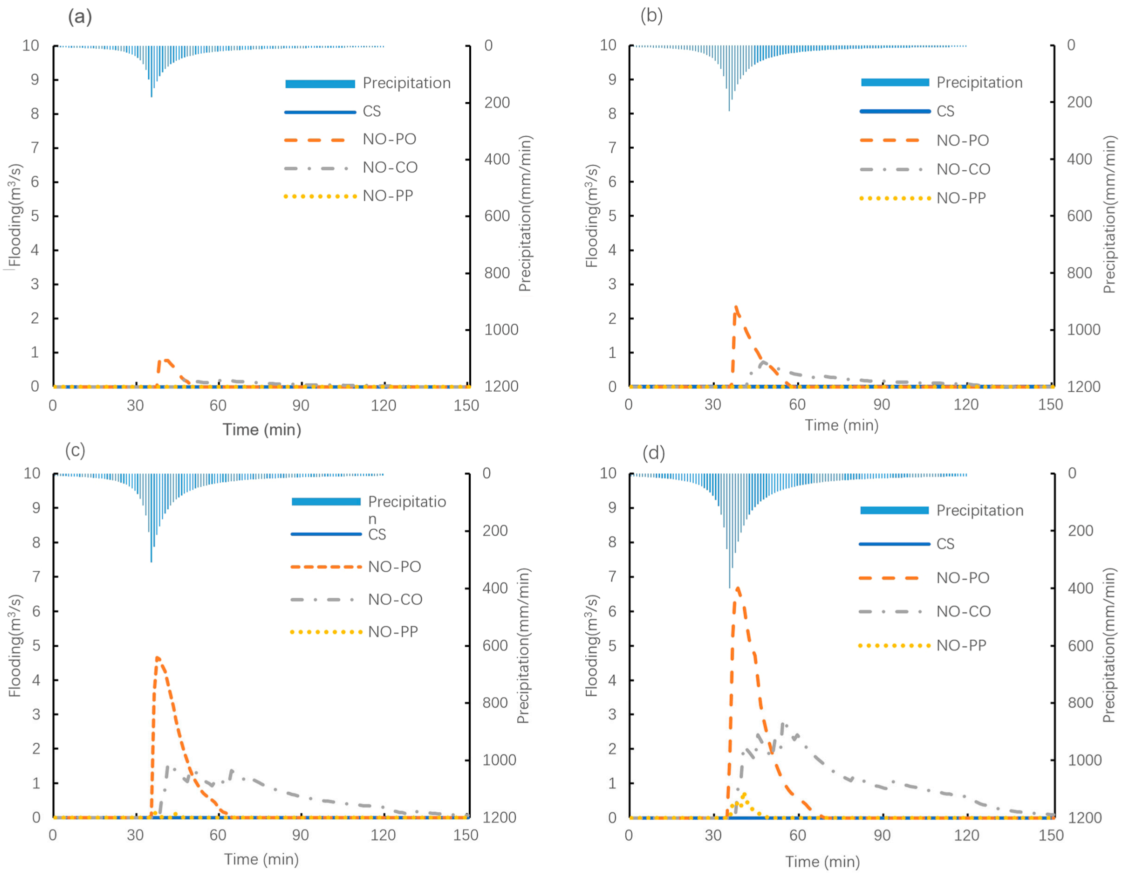


**Figure 8.** Comparison of flooding of four scenarios for different rainfall return periods: (**a**) 2-year return period; (**b**) 5-year return period; (**c**) 20-year return period; and (**d**) 50-year return period.

### 3.4. Outflow

As can be seen from Figure 9, the outflow of No-PO is significantly greater than that of the other three scenarios, because without the water storage facility of the pond, most of the surface runoff in Zhuge Village flows out. No-PP is similar to CS in that their total outflow is very small. As the rainfall return period increases, the outflow of these two scenarios also increases accordingly, and the gap with No-PO gradually decreases. This is because as the rainfall increases, once the pond is full, it no longer has the capacity to store water, so the runoff flows out. The outflow of No-CO mainly comes from the sub-catchment area around the outlet. Without the connection of conduits, the runoff in the rest of the catchment area only flows towards the nearby pond, so the outflow of NO-CO is the lowest.

In terms of outflow time, the outflow time of No-PO is about 83 min earlier than that of CS (20a), indicating that the ponds play a significant role in slowing down the outflow time of the village. This is due to the large cache capacity of the pond, which can regulate the outflow time of runoff. It is worth mentioning that the outflow also reflects the regulating effect of ponds on runoff. Ponds can reduce downstream runoff and alleviate the runoff of the larger areas, although they have no significant impact on the surface runoff within the village system.

### 3.5. Storage

The comparison of total rainwater storage in the four scenarios is shown in Figure 10. Based on the simulation results of the different rainfall return periods, 2a, 5a, 20a, and 50a, it is obvious that No-PO hardly stores rainwater, and its water storage capacity is far less than that of the other three scenarios (all of which have ponds). It can be seen that ponds are the most critical water storage facilities. The amount of water stored in No-PP is the largest, followed by CS, and the amount in No-CO is slightly less than the previous two.

Due to the low infiltration of rainwater in No-PP (only green spaces have infiltration), the total amount of runoff is relatively large, so the amount water storage is the largest. In No-CO, with losing the function of rainwater transmission, the full ponds can not transmit rainwater downstream, resulting in some ponds overflowing, while others are not yet full, so the water storage of No-CO is not large nor sufficient.

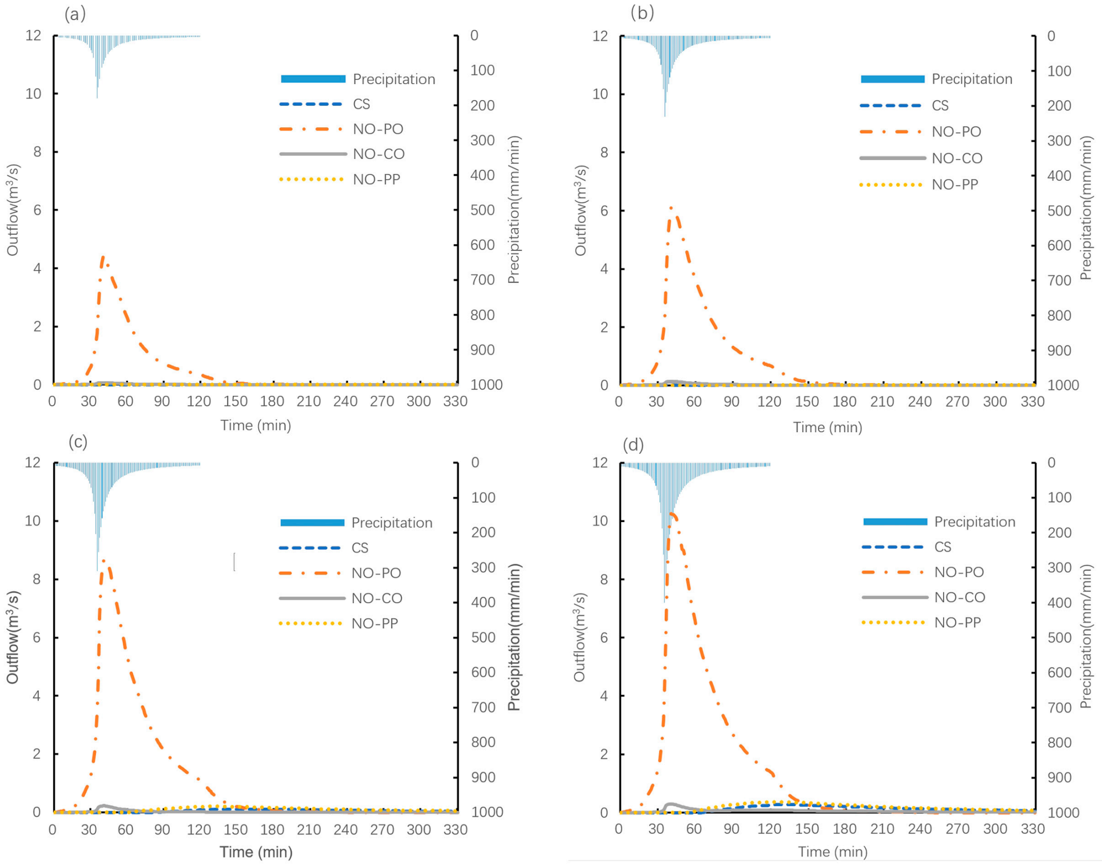


**Figure 9.** Comparison of outflow in four scenarios for different rainfall return periods: (**a**) 2-year return period; (**b**) 5-year return period; (**c**) 20-year return period; and (**d**) 50-year return period.

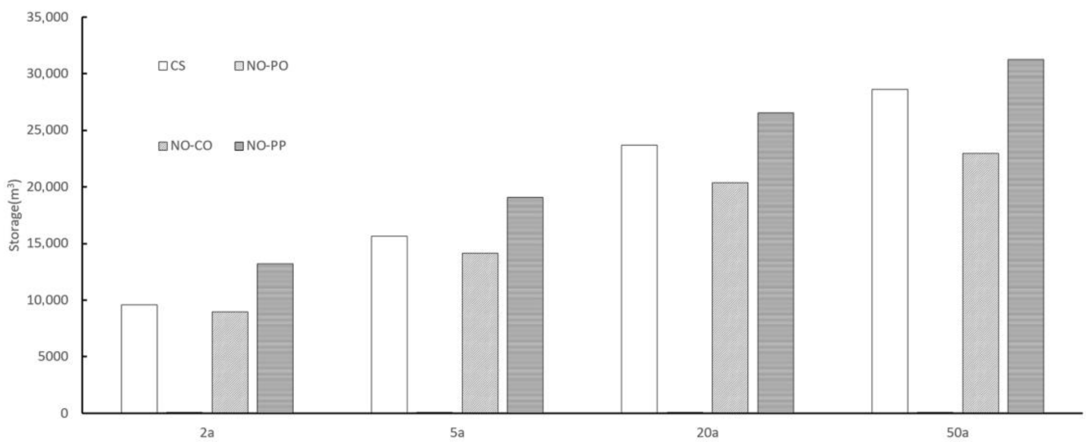


**Figure 10.** Comparison of runoff storage in four scenarios for different rainfall return periods. 2a refers to a 2-year return period; 5a refers to a 5-year return period; 20a refers to a 20-year return period; and 50a refers to a 50-year return period.

The ratio of total water storage to total runoff can reflect the utilization rate of rainstorm runoff in village. For the four return periods of 2a, 5a, 20a, and 50a, the runoff utilization rate of CS is 100%, 100%, 93.69%, and 90.14%, that of No-CO is 78.77%, 75.58%, 66.75%, and 59.84%, that of No-PP is 100%, 98.38%, 91.02%, and 87.58%, and that of No-PO is 0.05%, 0.03%, 0.02%, and 0.01%, respectively (Figure 11). From the perspective of runoff utilization efficiency, No-PP is equivalent to CS, with over 90% of the runoff stored for daily use and irrigation. However, as the rainfall intensity increases (the return period increases), ponds become saturated to varying degrees, resulting in a decrease in storage capacity and a gradual decrease in runoff utilization efficiency. The runoff utilization rate of No-CO is between 60% and 80%. Due to the removal of conduits, runoff cannot be evenly stored by the ponds in the village, resulting in a significant loss of runoff due to flood overflows. Therefore, the amount of stored runoff is relatively small. The runoff utilization rate of No-PO is almost zero, because the ponds are important water storage facilities, and the village almost loses its water storage function after the ponds are removed.

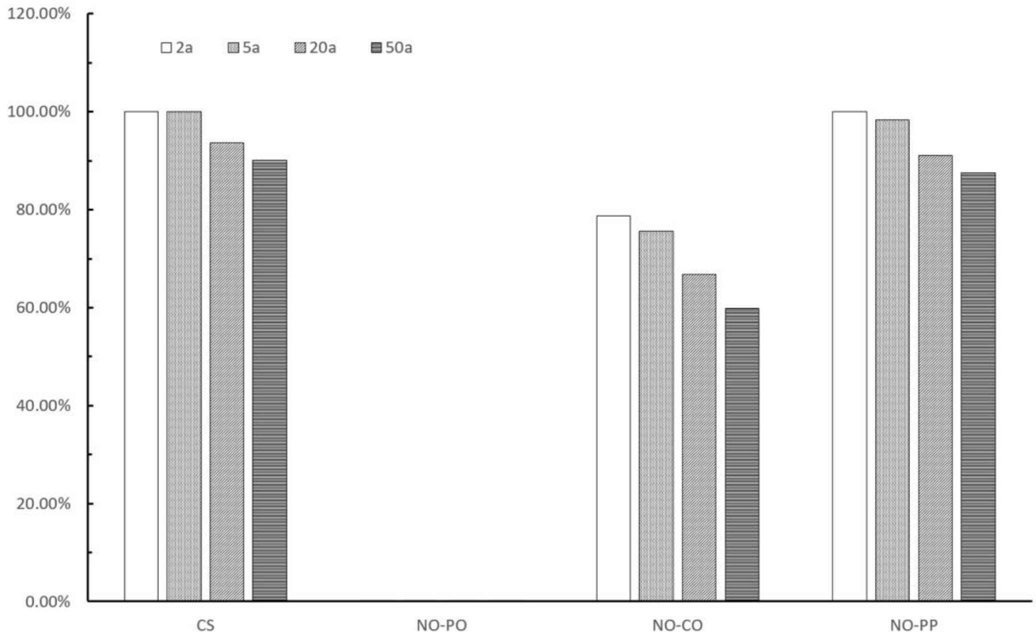


**Figure 11.** Comparison of the runoff utilization rate in four scenarios for different rainfall return periods. 2a refers to a 2-year return period; 5a refers to a 5-year return period; 20a refers to a 20-year return period; and 50a refers to 50-year return period.

It can be seen that ponds are the key facilities for storing rainwater (runoff utilization), and conduits help to balance the collection and storage of rainwater in different ponds and also have a certain role.

## 4. Discussion

### *4.1. Function Analysis of Stormwater Management Facilities in Zhuge Village*

Taking the 20-year return period (20a) as an example, in Zhuge Village, compared with CS, the changes in runoff, peak runoff, water volume, discharge, water storage, and other indicators in the three scenarios, No-PO, No-CO, and No-PP, are shown in Table 8 below.

After removing the pond (No-PO) in Zhuge Village, the runoff and peak runoff display little change, which shows that the pond has little effect on the surface runoff in a small watershed. The outflow and flooding increased significantly, and the outflow time of the runoff to the village was advanced by 83 min, indicating that the pond has a good runoff cache function. This is consistent with the research results of Jiang et al. [45] on the impact of retention ponds on runoff hydrology. Without the cache function of the pond, the problem of flooding in Zhuge Village is serious. Due to the rapid runoff, flooding occurs in narrow sections of the conduits and low-lying areas. Ponds are the main water storage facility in villages. After removing the ponds (No-PO), the rainwater storage is reduced by 23,676.5 $m^3$ compared with CS, with a reduction ratio of nearly 100% (Table 8). Most of the rainwater runoff is drained away, and the water storage function of the village almost disappears.

**Table 8.** Changes in hydrological indicators of three hypothetical scenarios (No-PO, No-CO, and No-PP) compared to CS (when the rainfall return period is 20 years).

| | Total Runoff ($m^3$) | Total Runoff Change (%) | Peak Runoff ($m^3$/s) | Peak Runoff Change (%) | Flooding Volume ($m^3$) | Flooding Volume Change ($m^3$) | Flooding Duration | Flooding Duration Change | Outflow ($m^3$) | Outflow Change (%) | Outflow Start Time | Outflow Start Time Change | Storage ($m^3$) | Storage Change (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CS | 25,275.6 | — | 14.31 | — | 0 | — | 0 | — | 1576.8 | — | The 84th minute | — | 23,681 | — |
| No-PO | 25,284.6 | 0.0% | 14.36 | 0.3% | 3154.2 | 3154.2 * | 29 min | 29 min * | 22,131 | 1303.5% ** | The 1st minute | 83 min earlier ** | 4.5 | −100.0% ** |
| No-CO | 30,508.2 | 20.7% ** | 16.06 | 12.2% * | 4315.2 | 4315.2 ** | 171 min | 171 min ** | 521.4 | −66.9% * | The 13th minute | 71 min earlier * | 20,363 | −14.0% * |
| No-PP | 29,146.8 | 15.3% * | 21.20 | 48.1% ** | 39 | 39 | 3 min | 3 min | 2572.2 | 63.1% | The 63rd minute | 21 min earlier | 26,530 | 12.0% |

Note: The above table describes the changes in hydrological indicators such as total runoff, peak runoff, flooding volume, flooding duration, outflow, outflow start time, and rainwater storage volume of three hydrological scenarios (No-PO, No-CO, and No-PP) compared to CS. ** indicates the value with the largest change, and * indicates the value with the second largest change for each hydrological indicator.

After removing the conduits (No-CO) in Zhuge Village, the runoff and flooding increase obviously, the peak runoff also increases, and the rainwater storage decreases (Table 8). Since the SWMM mainly simulates surface runoff, after removing the conduits, the runoff from the sub-catchment that originally flowed into the nearby conduit node (runoff outlet of sub-catchment) flows into the next sub-catchment and eventually enters a pond relatively far away, which increases the distance of surface runoff, and the total runoff and peak runoff increase significantly. Therefore, conduits play the role of organizing confluence and orderly drainage, which can reduce the surface runoff and runoff peak. As the main rainwater transmission facility of the village, the removal of the conduits results in the loss of the rainwater transmission function of the village and poor drainage. Therefore, flooding in No-CO is the most serious among the four scenarios, as water cannot easily be discharged after flooding and the flooding time is the longest (the duration of flooding in Zhuge Village was 171 min for 20a). The loss of the transmission function also affects the water resource balance function of the conduits. Full ponds cannot be drained downstream, resulting in the overflow of these full ponds, while other ponds are not full, resulting in insufficient water storage, with the amount of rainwater storage for No-CO being about 14% lower than that for CS. In No-CO, the village outflow is only the runoff from the sub-catchments around the village outlet (runoff from other sub-catchments flows into nearby ponds), so the outflow is small.

After removing permeable pavement (No-PP), both runoff and peak runoff increased, especially peak runoff (Table 8). Because permeable pavement can increase rainwater infiltration, it has a better slowing effect on runoff and runoff peak, so removing permeable pavement will significantly increase runoff peak and runoff and increase pond storage. In addition, in the low rainfall return period (2a and 5a), the total runoff of No-PP is the largest, while in the high rainfall return period (20a and 50a), the total runoff of No-PP is lower than that of No-CO, and the percentage of the difference between CS and No-PO also decreases. The reason for this is that the influence of permeable pavement on runoff is greater in the low rainfall return periods. However, when the rainfall intensity is too high, the soil infiltration rate in permeable pavement area is close to the minimum value (soil is close to the state of full saturation), and the mitigating effect of permeable pavement on runoff is reduced. Therefore, the total runoff of the other three scenarios gradually approaches or even exceeds that of No-PP, which is consistent with many research findings on the impact of permeable pavement (a type of low-impact development (LID) facility) on runoff [4,46].

Given the above analysis, facilities such as ponds, canals, and permeable pavement play important roles in the stormwater management of Zhuge Village. The biggest function of the ponds is to improve the water storage capacity of the village and improve the utilization rate of runoff. The cache function of ponds can avoid the rapid accumulation of runoff, delay the time of runoff outflow, and reduce runoff in a larger area. The main function of the conduits is to transport rainwater, achieve rapid drainage, and help to avoid or alleviate flooding; conduits also have the function of organizing confluence and balancing water resources, helping to alleviate runoff and increase rainwater storage. Permeable pavement, by increasing rainwater infiltration, can effectively alleviate peak runoff and runoff, reduce rainwater outflow, and improve rainwater utilization efficiency.

### *4.2. Analysis of the Stormwater Management Mechanism in Zhuge Village*

The stormwater management in Zhuge Village mainly relies on a rainwater regulation system comprising facilities such as ponds, canals, and permeable pavement. Each facility has a series of specific measures to achieve the functions of "Orderly Rainwater Collection", "Rapid Drainage", and "Sufficient Rainwater Storage" in the village, as shown in Figure 12.

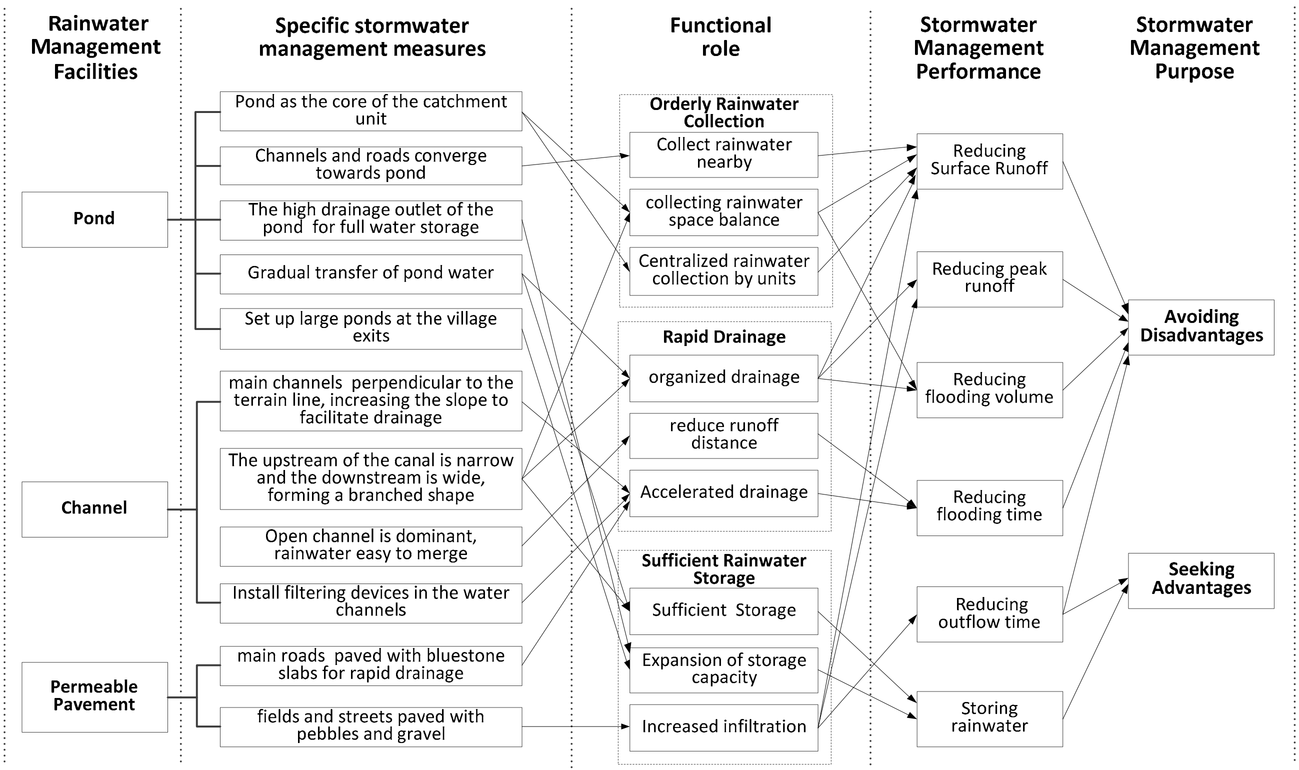


**Figure 12.** Analysis framework of stormwater management mechanisms in Zhuge Village.

(1) Orderly rainwater collection: Nineteen ponds in Zhuge Village are evenly distributed among the low-lying areas of the village, forming many catchment units with ponds as the core. These ponds have a large rainwater capacity, and each pond can basically contain runoff from the surrounding sub-catchment, alleviating the threat of local heavy rainfall. This distribution pattern of ponds is similar in the design and construction of percolation ponds in southern India [47]. This is an effective method for fully collecting rainwater from the catchment area, indicating that traditional ecological knowledge has reference significance for modern construction. The main roads and conduits within the catchment unit converge towards the pond, facilitating the orderly and rapid collection of rainwater along the conduits and canals towards the pond. Through the rational layout of ponds and canals in Zhuge Village, the aims of organizing the confluence effectively, reducing the confluence distance of rainwater, and collecting rainwater space balance can be realized.

(2) Rapid drainage: The water canals are important rainwater transmission facilities in Zhuge Village. Most of these canals are set perpendicular to the terrain line, so the slope

of the canals is increased through elevation changes to improve the drainage speed of the conduits [24]. The upstream canals are narrow, while the downstream canals are wider, forming a reasonable and orderly branch canal system, which is conducive to organized drainage. Most of the canals are open, which is convenient for the surface rainwater to enter and reduce the runoff distance. Multistage stone filter devices are also arranged at intervals in the canals, and the inlet of the hidden ditch is filtered with a grate to prevent garbage from blocking the water canal and reducing drainage capacity. The main roads are often paved with bluestone slabs, which is conducive to rapid drainage. Through these measures, a smooth and organized drainage canal network is formed in Zhuge Village to achieve the purpose of rapid discharge of storm runoff. This practice of using canals and roads for drainage is relatively common in traditional villages in hilly areas of southern China [16,24].

(3) Sufficient rainwater storage: Ponds are the main water storage facilities in Zhuge Village. In order to fully retain rainwater, the outlets of the ponds are generally higher. The ponds are connected by canals. When the upstream pond is full, the overflow water will flow to the downstream ponds until it reaches the three ponds (Pond 17, Pond 18, and Pond 19; see Table 1) at the exits of the village. The three ponds are obviously larger than the internal ponds, which expands the water storage capacity and thus realizes the purpose of adequately collecting and storing rainwater. According to the SWMM simulation, the multi-pond system in Zhuge Village can store 100% of the runoff for a 5-year return period rainstorm, while 90% of the runoff can still be absorbed for a 50-year return period rainstorm. This is close to the results of Zhe et al.'s study [21], showing that the multi-pond system in Liukeng Village can accommodate 83.0% of the runoff at the maximum recorded daily rainfall intensity. The pavement materials of the fields and streets in the village are mainly pervious pavement, such as pebbles and gravel, which can increase the infiltration of rainwater and slow down the runoff (about 15.3% of the runoff is reduced for 20a; see Table 8).

Through a series of measures related to rainwater collection, drainage, and storage, Zhuge Village has achieved the goal of reducing surface runoff, reducing peak runoff, reducing flooding and time, reducing outflow and time, and fully storing rainwater. It meets the needs of rapid flood discharge and runoff-sufficient storage in Zhuge Village and achieves the purpose of "seeking advantages and avoiding disadvantages" in relation to rainstorms (see Figure 12). Compared with previous qualitative studies on the ecological knowledge regarding stormwater management in traditional villages, this study, by means of quantitative simulation, evaluated the functional effects of traditional stormwater management facilities and measures and their impacts on runoff hydrology (runoff, outflow, storage, flooding, etc.), which can more accurately evaluate the efficiency and value of these facilities and measures.

## 5. Conclusions

This paper aims to analyze and reveal the traditional ecological knowledge regarding stormwater management in traditional Chinese villages through quantitative methods. Zhuge Village, a typical traditional village in the shallow, hilly region of South China, is taken as a case study. The SWMM is used to simulate and quantify the rainstorm hydrological process in Zhuge Village. Three hypothetical scenarios are set up in this study: the No Pond Scenario (NO-PO), the No Canal Scenario (NO-CO), and the No Permeable Pavement Scenario (NO-PP). The function and efficiency of the stormwater management facilities such as ponds, canals, and permeable pavement in Zhuge Village are quantitatively evaluated by comparing the three hypothetical scenarios with the actual Current Scenario (CS) regarding the total runoff, peak flow, flooding, outflow, and storage. The main findings are as follows:

(1) The artificial rainwater regulation system composed of ponds, canals, and permeable pavement can play a dual role in alleviating rainstorm disasters and fully storing rainwater, achieving the flexible allocation of rainwater resources. It can effectively alleviate the problem of uneven time and space regarding local rainfall in shallow, hilly areas, while

avoiding floods and ensuring year-round living and irrigation water resources. This reflects the traditional ecological wisdom of residents in adapting to the local natural environment.

(2) Ponds are the main water storage facilities of the village, responsible for the main rainwater storage function. After removing the ponds (No-PO), the water storage capacity approaches zero. Ponds have little influence on the surface runoff, but can effectively reduce total outflow, delay outflow time, and reduce flooding volume. After removing the ponds (No-PO), the outflow and flooding volume in Zhuge Village increases significantly, and the outflow time advances by 83 min.

(3) The main function of the canals is to transport rainwater and facilitate rapid drainage, thereby alleviating flooding problems. After removing the canals (No-CO), Zhuge Village experiences the most severe flooding problems and the longest duration of flooding (171 min in 20a). The canals also have the function of balancing water resources. After removing the canals (No-CO), the full ponds cannot drain downstream, resulting in insufficient storage of the downstream ponds, and the total rainwater storage in Zhuge Village is reduced by about 14% (20a).

(4) Permeable pavement can increase rainwater infiltration, effectively alleviate peak runoff and runoff, reduce rainwater outflow, and improve rainwater utilization efficiency.

Due to the complexity and uncertainty of stormwater management, previous studies on the ecological knowledge of rainwater management in traditional Chinese villages mainly rely on experience and qualitative analyses. Although the basic ideas, principles, and strategies of rainwater management can be roughly clarified, it is difficult to accurately quantify and evaluate the effectiveness of rainwater management facilities and measures. Based on the SWMM, this study not only quantifies and simulates the runoff, flooding, outflow, and rainwater storage in a village during a rainstorm but also quantifies the functional performance of each stormwater management facility, which helps to accurately reveal the traditional ecological knowledge regarding stormwater management hidden in traditional villages and provide a scientific basis for the reasonable construction and sustainable development of villages.

The SWMM is mainly used in urban areas and is rarely applied in rural areas. In this study, the SWMM is introduced to explore the construction and simulation of stormwater management models in a traditional village, providing a new analytical tool for the study of water management in a traditional village and expanding the application scope of the SWMM.

## 6. Research Limitations

In this study, the modeling and simulation work of the SWMM were carried out in the absence of real data. The comprehensive runoff coefficient of the study area was used as a calibration target for model parameter calibration. Using this method, the "satisfactory solution" of model parameter calibration can be obtained, but it is not the only optimal solution, and the simulation result is only a "similar" real situation or a "different parameter and same effect" with the real data. This model could be further verified by installing a system of rain gauges and a sensor to measure stream discharge at the outflow in the future.

**Author Contributions:** Conceptualization, J.L., C.T. and W.Z.; methodology, J.L. and C.T.; software, J.L. and C.T.; investigation, J.L. and C.T.; resources, J.L. and C.T.; data curation, C.T. and J.L.; writing—original draft preparation, J.L. and C.T.; writing—review and editing, C.T.; visualization, J.L.; supervision, W.Z.; project administration, C.T. and J.L.; funding acquisition, C.T. and J.L. All authors have read and agreed to the published version of the manuscript.

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