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Assessing the Performance of Permeable Pavement in Mitigating Flooding in Urban Areas

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Abstract: In the case of rapid urban development, the impact of extreme climates on the world is gradually increasing, resulting in frequent flood events. However, Taiwan is still in the stage of urban development, and it is necessary to develop more roads. Therefore, determining how to reduce the impact of road engineering on the environment is one of the major issues currently faced. Therefore, a demonstration road of a general pavement and a permeable pavement was built in Dahua North Street, Taoyuan City, Taiwan, and rainwater was stored in a central irrigation ditch and a permeable pavement through an innovative construction method for reuse in agricultural irrigation. In addition, monitoring instruments and management systems were built, and the flow law formula was established, with R^2 greater than 0.9. The actual discharge and peak discharge of the permeable pavement and general pavement were analyzed. According to the data analysis results, it can be seen that the permeable pavement can effectively reduce the peak discharge of 60~75%, which not only can achieve the benefit of low-impact development but also can reuse rainwater. The patent application can be used as an example for the application of permeable pavement in Taiwan in the future.

Keywords: permeable pavement; monitoring instruments and management systems; flow law formula; low-impact development

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Citation: Lee, Y.-T.; Ho, M.-C.; Chiou, Y.-S.; Huang, L.-L. Assessing the Performance of Permeable Pavement in Mitigating Flooding in Urban Areas. *Water* **2023**, *15*, 3551. https://doi.org/10.3390/w15203551

Academic Editors: Dafang Fu, Haifeng Jia, Jiangyong Hu and Wei-Shan Chen

Received: 8 September 2023
Revised: 6 October 2023
Accepted: 9 October 2023
Published: 11 October 2023

1. Introduction

As Taiwan is still in the stage of urban development, determining how to reduce the impact of urban floods brought by urbanization is a current issue facing Taiwan. Asif Iqbal [1] used the design of permeable pavement to reduce the impact of urban floods. Therefore, this paper hopes to explore the low-impact development benefits of a permeable pavement, which can reduce the burden of the overall drainage system under extreme climate conditions and then reduce the occurrence of disasters. Mariacrocetta Sambito [2] studied the literature on previous pavements in the past and found that there were few actual studies on the site in the past, and there was no long-term rainfall event to confirm the benefits of a pervious pavement. Therefore, this paper built a pervious pavement and a general pavement on the site and established a real-time monitoring system for management to conduct long-term data analysis.

Before the establishment of the demonstration road with permeable pavement in this study, relevant studies at home and abroad tested the permeable pavement and monitored its drainage flow data to understand the benefits of permeable pavement in reducing flood peak flow. Therefore, this study first discusses the results of relevant domestic and foreign test roads, hoping that the analysis of this demonstration road can be used as support for past studies and carry out the extension of the discussion, making up for the past research. In the past, there have been many studies on permeable pavements. Alharbi, F applied porous clay bricks mixed with bran as a permeable pavement, which can reduce pollutants and surface runoff [3]. Vaillancourt used a permeable intermingled concrete pavement (PICP) in urban areas [4] and discussed its benefit of reducing peak flood flow. After 12 months of monitoring, it was found that PICP could effectively reduce surface runoff by 26% to 98%, and it was found that the use of a more permeable soil subgrade would be more effective. Lin Wei Hong established a porous asphalt concrete pervious pavement and a general asphalt concrete pavement on-site [5], and the research results show that the water retention of the pervious pavement can be increased by approximately 35% to 65% compared with a general asphalt concrete pavement. The efficiency of low-impact development in two regions of Indiana, USA [6], was evaluated and analyzed in six sets of scenarios, including rainwater storage tanks and a permeable pavement with different proportions. The results of monitored runoff and water retention showed that under the above scenarios, low-impact development could reduce surface runoff by 2% to 12% in the two study areas. It can reduce urban flooding caused by heavy rainfall and water fog caused by frequent rain. Referring to the research results of permeable pavement in Xindian [7], four different permeable pavements were built in Xindian, and pervious concrete, porous asphalt concrete, grass-planting brick, and pervious brick were used as permeable pavement materials. It was found that the four pavement types could effectively reduce flood peak time, and the results were as follows: pervious concrete > porous asphalt concrete > grass-planting brick > permeable brick. In the past, scholars built permeable pavements on Arizona highways [8] and built monitoring instruments such as rain meters, flow meters, and moisture content meters to collect on-site data and analyze the data during rainstorms. It was found that the permeable pavement could effectively retain water after rainfall, and upon inspection of the pavement on site after rainfall, it was found that permeable pavement could dissipate surface runoff more quickly. The general pavement will have a water phenomenon. Korean scholars built permeable pavement in Seoul [9] and built on-site monitoring instruments and found that permeable pavement can effectively reduce surface runoff by 30–65%. Another study established a porous asphalt concrete bicycle path and pervious concrete brick sidewalk in Taipei City [10] and imported the field test data into SWMM for simulation analysis. The results showed that when heavy rain fell, pervious pavement could effectively reduce surface runoff by 35% to 41%.

To sum up, previous studies can effectively reduce surface runoff by analyzing the flow of permeable pavement. However, most studies still focus on the analysis of surface runoff and do not analyze the actual discharge after rainfall of permeable pavement and general pavement. However, Gauss found in his study [11] that the setting of low-impact development can store part of the rainwater of a rainfall event. It will delay its outflow time, but for long-delay heavy-rainfall events, the initial storage of rainwater in the low-impact development will be drained along with the subsequent rainfall of the long-delay rainfall event, resulting in increased drainage. Therefore, this study built permeable pavement and general pavement, used a central irrigation ditch and permeable pavement to reduce the actual discharge through innovative construction methods, buried rain meters and flowmeters under general pavement and permeable pavement, and established a flow law formula, which can calculate the actual discharge and flood peak discharge of permeable pavement and general pavement for a long time. The benefits of pervious pavement in reducing peak flood flow and reducing the burden on the overall drainage system during heavy rainfall are confirmed. The flow chart of this paper is shown in Figure 1.

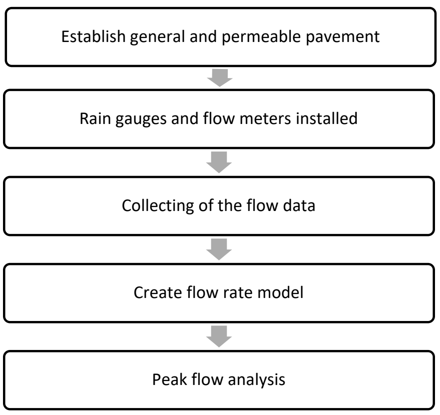


Figure 1. Research Flow Chart.

2. Materials and Methods

2.1. Difference between Permeable Pavement and Other Pavement

The so-called permeable pavement system applies materials with good permeability and high porosity to the surface layer, foundation, and bottom layer of the pavement, so that rainwater flows through the pavement with excessive porosity and directly penetrates the subgrade soil, and then the water returns to the ground through the action of atmospheric water circulation. The permeable material of the drainage pavement is used as the surface layer, and the rainwater penetrates through the surface layer and then enters the side ditch. The conventional pavement drains rainwater into the side ditch by running on the pavement surface.

As can be seen from Figure 2, three types of pavement, general pavement, drainage pavement, and permeable pavement, are used to discharge rainwater from the road surface. The traditional dense-graded pavement emphasizes the concept of rapid drainage, so the pavement design adopts an inclined angle to direct rainwater into the roadside water collection facilities. The surface layer of the drainage pavement has high porosity, so most of the rainwater can first infiltrate into the surface layer and then be discharged by drainage facilities, such as the permeable pavement express lane in this study. The design principle of permeable pavement is roughly the same as that of drainage pavement, the only difference is that there is no permeable layer in the structure of permeable pavement, so rainwater permeates into the soil through the pores on the pavement, such as the permeable pavement slow lane in this study [12].

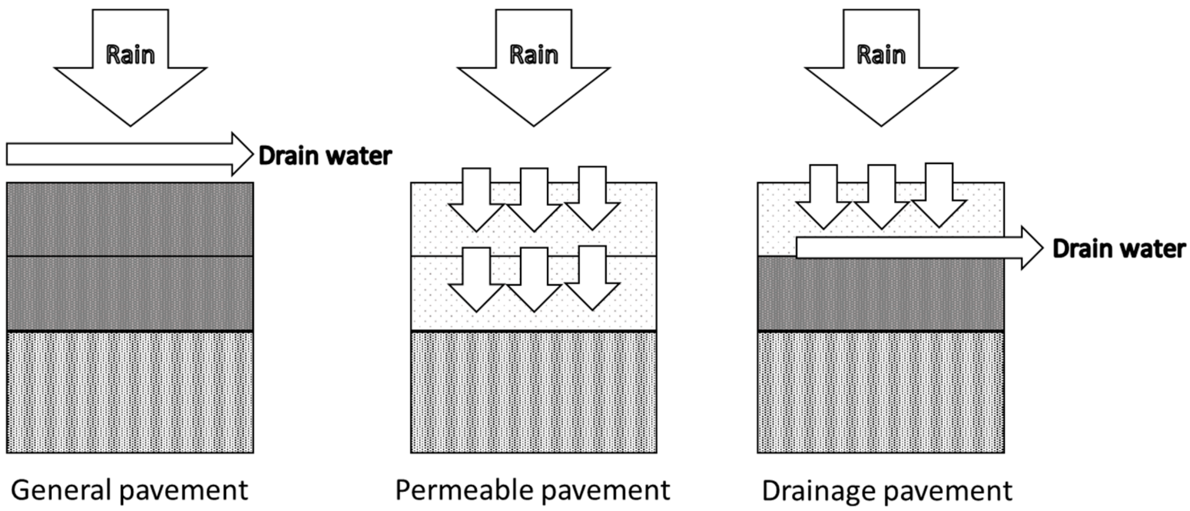


Figure 2. Comparison of permeable pavement with other pavements.

2.2. Test Road Setup

2.2.1. Introduction of Local Environment

1. Location: Dahua North Street, Luzhu District, Taoyuan City, Taiwan.
2. Water catchment area: It is divided into permeable pavement and ordinary pavement test sites. The dividing point is shown by the red dotted line in Figure 3. The ordinary pavement to the west of the red line and the permeable pavement to the east of the red line are approximately 200 m in length and 15 to 20 m in width.
3. The permeable pavement is further divided into the fast lane and the slow lane, aiming to divert traffic volume and enhance traffic safety. Each lane serves different types of vehicles, with the fast lane designed for regular cars and heavy vehicles, while the slow lane is designated for motorcycles, as shown in Figure 4.
4. Climatic conditions: Precipitation collected in the past three years is shown in Figure 5.

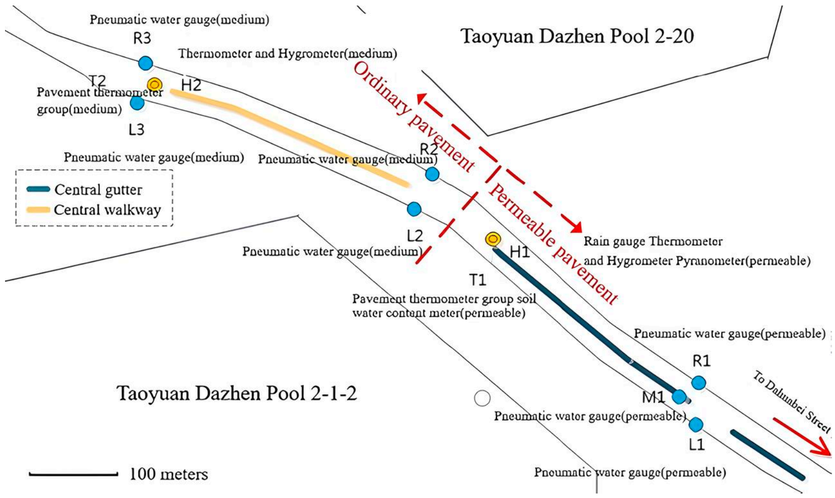


Figure 3. Test road scene situation.

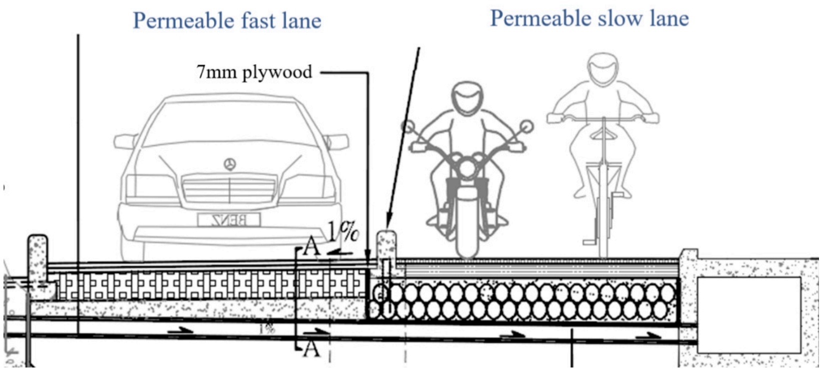


Figure 4. Design of permeable pavement.

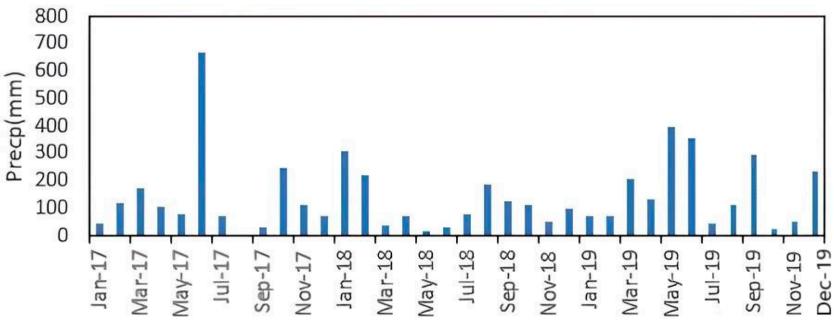


Figure 5. Precipitation in recent 3 years.

2.2.2. Sectional Configuration

The selection and construction of permeable pavement materials adhere to the guidelines outlined in the Urban Road Permeable Pavement User Manual [13] provided by the Urban Construction Department.

This study aims to evaluate the effectiveness of three types of pavement: A general graded asphalt concrete pavement, a permeable pavement for the fast lane, and a permeable pavement for the slow lane.

Figure 6 illustrates the cross-section configuration of the general graded asphalt concrete pavement and the permeable pavement for the fast lane and slow lane.

To analyze temperature variations, earth thermometers were buried within all three types of pavements.

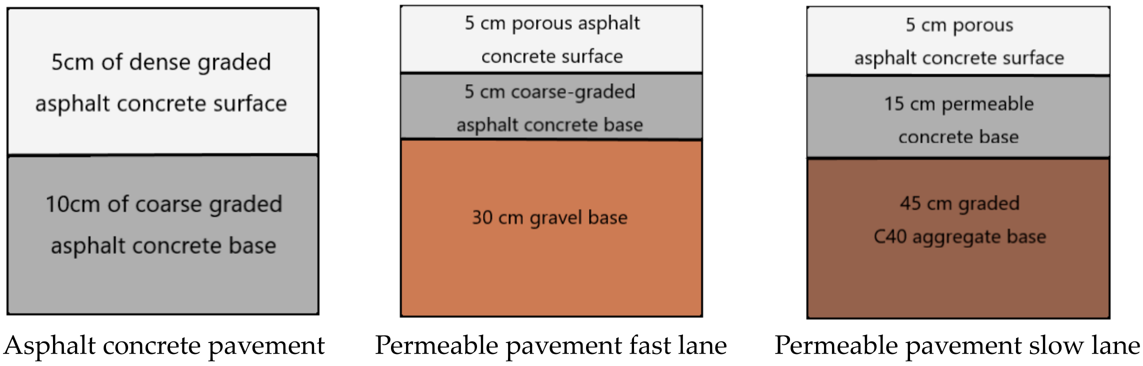


Figure 6. Section design of pavement.

2.2.3. Selection of Permeable Pavement Materials

1. Permeable pavement fast lane

The surface material used for the permeable pavement is porous asphalt concrete. Porous asphalt concrete generally refers to an asphalt mixture that retains over 15% porosity even after compaction. Its internal composition consists of interconnected continuous voids, allowing water to flow freely between them. According to the specifications, the water permeability coefficient should reach 10^{-2} cm/s [14].

The potential harm caused by water to asphalt concrete pavement has always been a topic of concern for pavement designers, as water retention on the asphalt concrete surface can jeopardize driving safety and pavement durability.

Due to its specific gradation, the porous asphalt concrete surface layer lacks fine materials to fill the gaps between particles, resulting in a high porosity. This allows water to flow freely between the gaps, swiftly removing precipitation and reducing the occurrence of surface water on the road.

Moreover, the rough surface of porous asphalt concrete pavement enhances its anti-skid ability, leading to reduced braking distances, decreased vehicle slippage, and improved driving safety.

Furthermore, research on the durability of porous pavement suggests that mixtures with smaller nominal particle sizes are more prone to clogging, potentially impacting the long-term durability of permeable pavement.

The pervious capacity of porous asphalt concrete can be evaluated through in situ pervious tests. According to the “Technical pointer for drainage paving” issued by the Japan Road Association [15], the individual measured value in an in situ pervious test should exceed 900 mL/15 s.

Porous asphalt concrete is used as the surface material for the permeable pavement express lane used in this paper. The porous asphalt concrete ratio is shown in Table 1, and relevant tests are carried out for the asphalt concrete mixture, all of which comply with the specifications in Chapter 02798 of the construction outline specification [14], as detailed in Table 2.

Table 1. Porous asphalt concrete ratio table.

Mesh No.	Passing Weight Percentage of Test Sieve (%)			
	Lower Limit Value	Experimental Value	Upper Limit Value	Conform to Specifications
1″	100	100	100	OK
3/4″	95	97	100	OK
1/2″	64	64	84	OK
3/8″	-	49	-	
No. 4	10	20	31	OK
No. 8	10	15	20	OK
No. 16	-	10	-	

Table 1. *Cont.*

Mesh No.	Passing Weight Percentage of Test Sieve (%)			
	Lower Limit Value	**Experimental Value**	**Upper Limit Value**	**Conform to Specifications**
No. 30	-	8	-	
No. 50	-	7	-	
No. 100	-	6	-	
No. 200	3	5.1	7	OK
Bitumen content (%)	4	5.1	6	OK

Table 2. Test results of porous asphalt concrete mixture.

Test Project	The Test Results	Specification Values
Stable value (kgf)	650	350
Mobility value (0.1 mm)	24	20~40
Porosity rate (%)	17	15~25
Dynamic stability value (times/mm):	2487	Over 1500
Retention strength index (%)	90	Over 75
Cantabria test (%)	16.8	Below 20
Vertical flow test (%):	0.12	Below 0.3
Permeability coefficient (cm/s)	0.11	Over 0.01

2. Permeable pavement slow lane

The porous asphalt concrete surface is used for the slow lane of the permeable pavement. The material properties are shown in Tables 1 and 2. In addition, pervious concrete and C40 are used as the bottom material.

- Permeable Concrete

Permeable concrete exhibits a porosity ranging from 20% to 35%. The high porosity enhances the water permeability and water retention capabilities of the permeable pavement. According to the specifications, the water permeability coefficient should reach 10^{-3} cm/s. The aggregates used in permeable concrete have a passing percentage of approximately 2% to 3% or less for the No. 4 sieve. Cylindrical specimens are cured at different ages: 1 day, 3 days, 7 days, and 28 days. Additionally, bending specimens are prepared for the 28-day curing period [13].

Various design methods are employed for permeable concrete, including the weight ratio method, volume method, and specific surface area method. For this study, the weight ratio method is used as the design method for permeable concrete. The proportions of aggregates, cement, mixing water, and admixtures are determined after confirming the effectiveness of the trial mix.

- Grade C40 Aggregate

Pao-Ching Chang carried out test paving of three permeable sections and general pavement on Longci Road, Zhongli City [16]. The surface layers of the three permeable pavement sections are all permeable asphalt concrete, and only the bottom material is different. Pervious concrete is used in Section 1, low-density pervious concrete in Section 2, and C40 permeable grade in Section 3. The flow analysis of each pavement after rainfall showed that three permeable pavements had the benefit of flood peak delay, namely, Section 1 (30 min), Section 2 (20 min), and Section 3 (40 min), in which C40 permeable grade was used as the bottom pavement with the best effect. Therefore, C40 was selected as the bottom material of permeable pavement in this paper.

The grade C40 aggregate used for the bottom layer exhibits higher porosity compared to the general graded layer, enabling effective water permeability. The aggregate standard grading for grade C40 aggregate is provided in Table 3 [17].

Table 3. The aggregate standard grading.

	Passing Weight Percentage of Test Sieve (%)						
	37.5 mm	**31.5 mm**	**25.0 mm**	**19.0 mm**	**12.5 mm**	**4.75 mm**	**2.36 mm**
C40	100~95	-	-	80~50	-	40~15	25~5

According to the recommended grading for C40 materials in Japan [18], the suggested particle content passing through the #8 sieve falls between 5% and 25%. For particle sizes that do not fall within the recommended range, a smooth and continuous curve is employed as the design gradation. Standard compaction tests are conducted using crushed stone-grade ingredients with three different fine particle contents of 5%, 15%, and 25% to determine their optimum moisture content (OMC).

Subsequently, permeability tests are performed to assess the permeability of various gradation combinations and evaluate their permeability.

- The material properties and test specifications of permeable pavement slow lanes are shown in Table 4.

Table 4. Properties of the material.

Project	Test Project	The Test Results	Specification Values
Porous asphalt concrete	Porosity rate (%)	17	15~25
	Permeability coefficient (cm/s)	0.11	Over 0.01
Grade C40 Aggregate	Porosity rate (%)	10	6~18
	Permeability coefficient (cm/s)	0.0103	3×10^{-3}~4×10^{-2}
Permeable Concrete	Porosity rate (%)	30	-
	Permeability coefficient (cm/s)	0.378	Over 10^{-3}

2.2.4. On-Site Monitoring Instrument

The monitoring instruments installed on permeable pavements and general dense-graded pavements in this study include the following monitoring instruments. The data collected by earth thermometers and thermometers are used for the analysis of this study.

In order to facilitate subsequent comprehensive analysis, this study set the monitoring frequency of various monitoring instruments to obtain 1 piece of data every 10 min, so 144 data will be collected in one day:

- Earth thermometers (soft adhesive type Thermalpas NR-40-MS).
- Flowmeter (German NIVUS PCM 4 portable ultrasonic flowmeter).
- Thermometer.
- Rain Gauge,

In this study, it is estimated that the instruments to be set on Dahuabei Street in Luzhu District are the pressure water level gauge (eYc L051 water level sensor), earth thermometer, and atmospheric thermometer.

Table 5 shows the buried settings of the equipment after the on-site survey. The research site is Dahua North Street, Luzhu District, the annual temperature is around 21 degrees, the annual average rainfall is approximately 10.8 mm/day, which is lower than the average rainfall in Taiwan, and the number of rainy days per year is approximately 140 days with more rain in summer but more rainy days in winter than in summer because of the strong northeast monsoon in winter.

Table 5. Equipment setting location.

Code	Equipment	Pavement
M1	Pneumatic water gauge	permeable pavement
R1	Pneumatic water gauge	permeable pavement
R2	Pneumatic water gauge	general pavement
R3	Pneumatic water gauge	general pavement
L1	Pneumatic water gauge	permeable pavement
L2	Pneumatic water gauge	general pavement
L3	Pneumatic water gauge	general pavement
T1	Pavement thermometer group	permeable pavement
T2	Pavement thermometer group	general pavement

We set up 4 sets of water level gauges in the side ditch of the permeable pavement and 1 set of water level gauges on the central safety island to measure the surface runoff and outflow runoff, and then calculated the net flow reduction and water retention capacity.

In addition, two sets of water level gauges are installed on the general asphalt concrete pavement to calculate the surface runoff, compare the rainwater effect between the permeable pavement and the general asphalt concrete pavement, and then evaluate the low-impact development effect of the permeable pavement.

The site construction diagram is shown in Figure 7.

Figure 7. Field configuration diagram of the flowmeter.

2.3. Water Flow Analysis Method

1. Flood peak reduction

The permeable pavement can use its full water retention, semi water retention, and institutional drainage mechanisms to reduce the runoff of the pavement; to achieve the benefits of low-impact development, its peak flow effect should be smaller than that of general asphalt concrete pavement.

Follow-up analysis is carried out using the aforementioned monitoring equipment conditions and calculating the runoff of permeable pavement and general asphalt concrete pavement on Dahuabei Street.

In addition, the on-site rain gauge is used to measure and analyze the rainfall, and the rainfall is measured through the rain gauge. Finally, the surface runoff and rainfall are used to calculate the flood peak reduction to evaluate the effect of low-impact development.

In this study, the flood peak flow is calculated as the reduction of the flood peak flow of the permeable pavement relative to the general asphalt concrete pavement, as shown in Equation (1).

$$\text{Peak Flow Reduction} = \text{General Asphalt Concrete Peak Flow} - \text{Permeable Pavement Peak Flow} \tag{1}$$

2. Flow rate determination method

The basic definition of flow rate is the volume of water (Wv) passing through each unit of time (t), which is called the flow rate (Q).

Based on the continuous equation, the flow rate through a certain cross-section can be obtained according to Equation (2) or Equation (3).

Since the channel cross-section is irregular and has no specific shape, the water-passing cross-section is divided into n small sections, and the flow qi of each small section is estimated according to the concept of Equation (4). The above concept can be expressed by Equations (4) and (5) and can be further divided into the mid-section method and the mean-section method.

The interrupted surface method assumes that the water passage section of the channel is composed of several different rectangular sub-sections, and the width of each sub-section is half the distance between the adjacent water depths. The corresponding sub-sectional area is shown in Equation (7), and the multiplication and accumulation are the total flow.

The average cross-section method treats the cross-section as composed of multiple trapezoidal sub-sections (as shown in Figure 8), and the average velocity of each sub-section is the average of the average velocity of the two adjacent vertical lines in Equation (8). The sub-sectional area is shown in Equation (9), and according to Equation (4), it can be accumulated into the total flow.

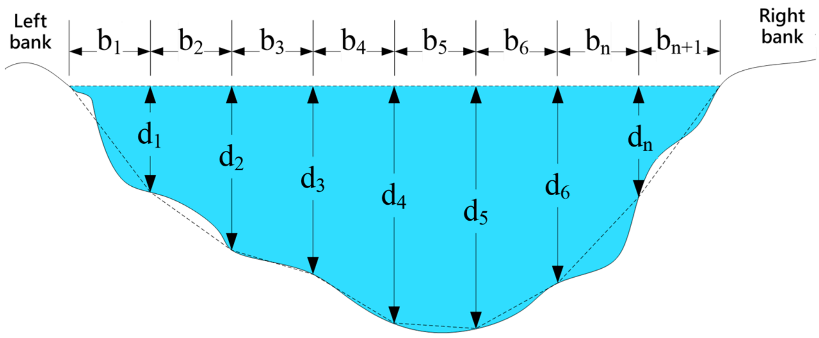


Figure 8. Schematic diagram of the mean section method.

Although the interrupted surface method has the advantage of simplicity, the accuracy is relatively low, while the average cross-section method is complicated but has the advantages of high accuracy (Chen Fengwen et al., 2012) [19].

$$Q = \int_A v dA \tag{2}$$

$$Q = V\mathrm{av} \bullet A \tag{3}$$

$$Q = a_1 v_1 + a_2 v_2 + a_3 v v_3 \ldots + a_n v_n \tag{4}$$

$$Q = q_1 + q_2 + q_3 + \ldots + q_n \tag{5}$$

In the formula: A is the cross-sectional area of the channel measurement surface, v is the flow velocity at any point in the cross-section of the flow zone, V_{av} is the average velocity of the water-passing cross-section, n is the number of divisions of the water sectional area, a_i is the area of the i-th smallest section, and v_i is the flow velocity of the i-th smallest section.

$$v_{\mathrm{mid}} = v_{\mathrm{av,i}} = v_{\mathrm{i}} \tag{6}$$

$$a_{\mathrm{mid}} = a_{\mathrm{i}} = bi \cdot di \tag{7}$$

$$v_{\mathrm{mean}} = v_{\mathrm{av,i}} = \frac{v_{\mathrm{i}} + v_{\mathrm{i+1}}}{2} \tag{8}$$

$$a_{\mathrm{mean}} = a_{\mathrm{i}} = \frac{(b_{\mathrm{i}} + b_{\mathrm{i+1}}) \cdot d_{\mathrm{i}}}{2} \tag{9}$$

where v_{mid} is the average velocity in sub-sections of the medium section method, v_{mean} is the average velocity in sub-sections of the average section method, a_{mid} is the sub-section area of the medium section method, and a_{mean} is the sub-section area of the average section method, as shown in Figure 8.

From the flow measurement and monitoring method, it can be seen that the velocity observation mainly functions to obtain the vertical average velocity of each sub-section.

This study uses the Acoustic Doppler Profiler (ADP), which is a device for directly observing the vertical profile flow velocity of the survey line.

The operation method and related principles of the Doppler flow meter are as follows.

The direct observation of the average vertical flow velocity can be obtained directly through the Doppler flowmeter without further correction or calculation (Chen Fengwen et al., 2012) [19].

Among various types of sonic flowmeters, ultrasonic is the most widely used, and its operating principle is the use of the Doppler effect.

The measurement data can be divided into the Acoustic Doppler Velocimeter (ADV) and the Acoustic Doppler Profiler (ADP) according to the range of sonar scanning.

The difference between the above two is that ADV can only measure the flow velocity of a single point, while ADP can measure the flow velocity of multiple points on a vertical line and can directly measure the flow velocity profile.

ADP is also widely used in stereotyped channel flow observation and has obtained excellent results (Chen Fengwen et al., 2008a; Chen Fengwen et al., 2008b) [20,21].

Hydrological information can obtain stable long-term data through automatic monitoring. In terms of flow, the flow (Q) and the water level (H) at a fixed position of a fixed water cross-section have a certain mathematical relationship.

Therefore, based on the establishment of the H–Q relationship, the water level (H) measured by the water level sensing element can be set up, and the flow information can be obtained through the conversion of the relationship between the water level and the flow rate (Q).

The above water level (H) parameter contains elevation information, so it can be applied to natural rivers where the bottom of the canal is easy to scour or silt, and the elevation changes or the shape in the satin surface is easy to change.

Therefore, the Water Resources Department applies this method to water level or flow measurement stations to obtain the flow information of different regions of each river basin at different times, as in Equation (10).

Since the local channel in this study is a fixed channel and the bottom elevation and section factors are fixed, the water level can be adjusted to the water depth, and the symbol is still represented as H.

The regression analysis of the quadratic equation of one variable is directly applied to establish the water depth (H)-discharge (Q) calibration formula, which is shown in Equation (11).

In order to avoid the occurrence of extreme values or negative values in the formula or the phenomenon of standing water level on-site, the regression analysis process sets the intercept to 0, and Equation (11) can be modified to Equation (12).

In order to avoid the occurrence of extreme values or negative values in the formula or the phenomenon of a standing water level on-site, the regression analysis process sets the intercept to 0, and Equation (11) can be modified to Equation (12).

Through the H–Q curve, the flow value corresponding to different water depths can be estimated.

Considering that there is no reliable water source at the test site of this study, the flow measurement can be adjusted according to different water depth conditions, so the Manning formula and the field-measured data are combined to estimate the H–Q equation.

The main consideration is that the theoretical value estimated by the Manning formula is mainly used initially, and the subsequent flow measurement with different water level conditions of the rainfall event is mainly used.

If there is a lack of flow measurement data at medium and high water depths, the theoretical flow data estimated by Manning's formula should be supplemented, and regression analysis will be carried out after integration.

It is important to ensure that the formula is based on the interpolation results obtained on a scientific basis or from field measurement data within the applicable range, rather than the uncertain extrapolation results.

$$Q = A(H_{EL} - H_B)^B;\ \text{Form of water level} \tag{10}$$

$$Q = CH^2 + DH \pm E;\ \text{Form of water depth} \tag{11}$$

$$Q = CH^2 + DH;\ \text{Form of water depth} \tag{12}$$

In the formula: A, B, C, D, and E are coefficients; Q is the flow rate (cms).

H is the water level in Equation (10) and water depth (m) in Equations (11) and (12).

H_{EL} is the water level, that is, the water surface elevation (m).

HB is the canal bottom elevation (m).

2.4. Construction of Permeable Pavement System

This system can be used to query the temperature monitoring data of Dahuabei Street, including real-time data and historical data.

The management of water level monitoring data can obtain water level information of the monitoring road at any time, and the information includes the monitoring station, equipment code, water level, and data measurement time, as shown in Figure 9.

The measured data use the change in water level and time to calculate the flow of its road and store the data for future queries.

Its main architecture includes a real-time information display, historical query, and flow calculation, while its functional architecture planning is shown in Figure 10 and is described as follows:

1. Real-time information query: The water level will be measured at each fixed time and uploaded to this system immediately,
2. Historical query: After the data are uploaded, they will be stored in the system. The data can be exported by entering the date to be inquired into the system.
3. Flow calculation: The flow is calculated by using the time and water level difference, and the flow between the permeable pavement and the general pavement is compared.

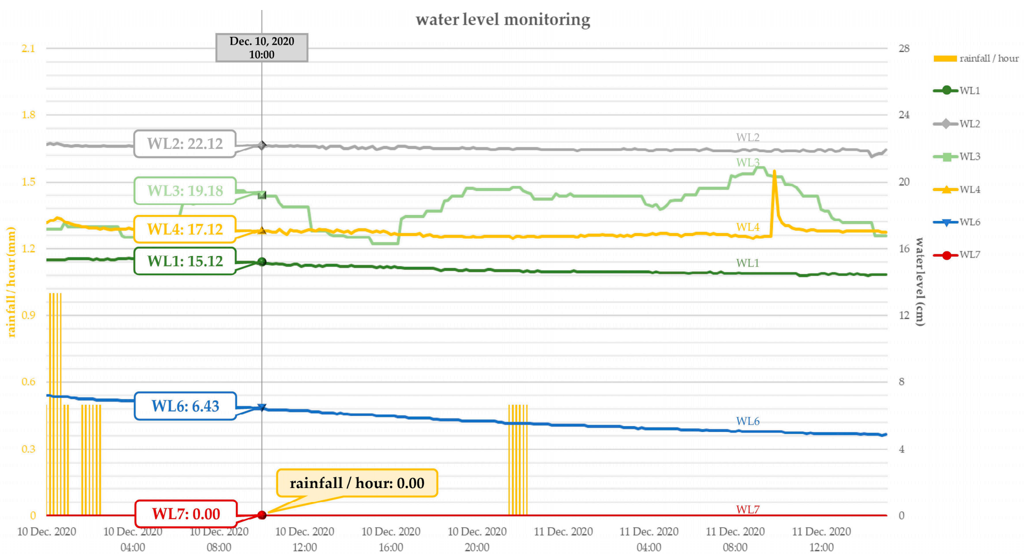


Figure 9. Line chart of historical data of water level monitoring.

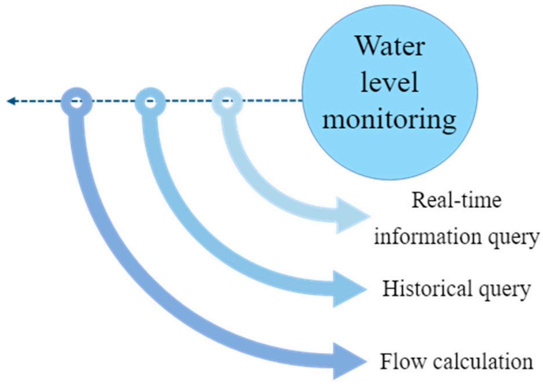


Figure 10. Functional Architecture of Water Level Monitoring.

3. Results

3.1. Analysis of Hydraulic Design Benefits for Permeable Pavement

Taoyuan City is known for its abundance of ponds, with a total of over 2800 ponds. The region also boasts a well-developed water irrigation system with extensive waterways. This project aims to leverage the existing water irrigation channels and transform them into dual-purpose channels that serve as irrigation channels during normal times and provide floodwater detention capacity during heavy-rainfall events. By implementing permeable or water retention measures, the decline in floodwater drainage function caused by development can be reduced and the ability to handle rainfall can be enhanced. Therefore, incorporating the concept of low-impact development into pavement engineering should be a top priority in creating a sustainable environment.

This project aims to achieve the benefits of low-impact development through the use of permeable pavement, focusing on enhancing the effectiveness of floodwater drainage. The design concept includes two key elements: The innovative design of central irrigation channels and the design of the permeable pavement itself to retain water. These two designs enable the permeable pavement to withstand rainfall intensities much higher than conventional pavements can tolerate.

3.1.1. Central Irrigation Channel Design

1. The innovative concept of permeable pavement in this project incorporates the design of central irrigation channels. The design involves directing runoff from rainfall into the central irrigation channels. The material is constructed using cobblestones, so the designer opted for a trapezoidal cross-section in the design, as shown in Figure 11. The collected rainwater is then diverted to adjacent farmland for irrigation purposes. This approach not only allows for the reuse of rainwater but also helps reduce the peak flow in the side ditches.
2. When the water level in the central irrigation channel exceeds 0.6 m, it will be discharged into the side ditches. Therefore, the calculated volume of rainwater that can be accommodated by the side ditches before being discharged is as follows: $Q_1 = 100 \times (1.3 + 1.63) \times 0.6/2 = 90\ m^3$.
3. In this paper, the innovative construction method is used to introduce rainwater into the central irrigation ditch and then introduce it into the surrounding farmland for reuse. Considering that the rainwater may contain harmful elements, the harmful elements are removed by referring to foreign methods. Among them, Azithromycin (AZM) is a harmful substance often found in water, which hurts both aquatic and terrestrial ecology. Muhammad Wahab [22] used activated carbon (AC) and magnetic activated carbon (MAC) to remove Azithromycin (AZM) from water. It can be seen from the research results that magnetic activated carbon (MAC) has the best effect on removing Azithromycin (AZM), so it can be introduced in the future to remove related harmful elements. Another common harmful element is arsenic (As), which

can cause serious harm to both human beings and the environment. Yongchang Sun [23] uses biochar and modified biochar to remove arsenic (As) from water, and biochar has achieved good results. Modified biochar can improve the removal rate more significantly. However, modified biochar still has production technical problems, so biochar can be applied first in the future, and then applied after modified biochar overcomes the technical problems.

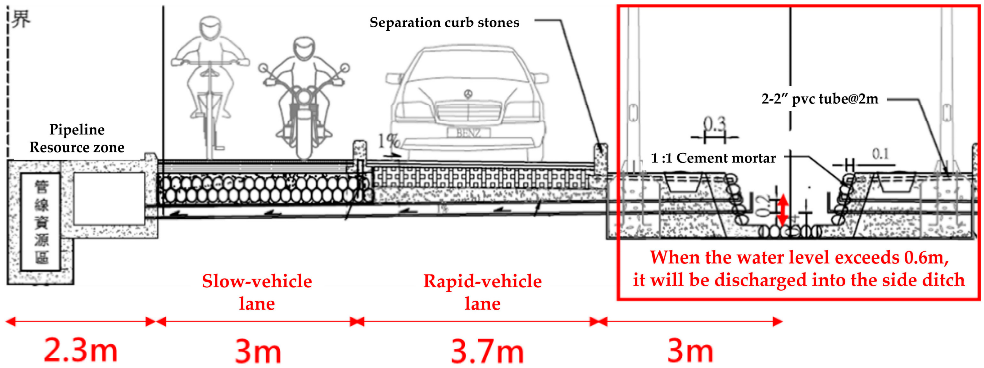


Figure 11. Central Irrigation Channel Design.

3.1.2. Design of Water Retention Capacity in Permeable Pavement Structure

1. Additionally, the permeable pavement itself has the ability to store rainwater within the void spaces between the aggregate particles. This helps to reduce surface runoff and decrease peak flow in the side ditches. Furthermore, the water retention benefits of permeable pavement contribute to mitigating the heat island effect. Among the different pavement sections, the permeable pavement used in slow-traffic lanes serves as the primary water retention area.
2. The structure of the permeable pavement used in slow traffic lanes serves as the primary rainwater storage space, and the section is shown in Figure 6 while the porosity is shown in Table 4.
3. The calculated volume of rainwater that can be accommodated by the road before being discharged into the side ditches (assuming a road width of 3 m and calculating based on a unit length of 100 m) is as follows: $Q_2 = 100 \times 3 \times 0.05 \times 17\% + 100 \times 3 \times 0.15 \times 30\% + 100 \times 3 \times 0.45 \times 10\% = 30\ m^3$.

3.1.3. Calculation of Overall Rainwater Storage Capacity

By utilizing the central irrigation channels and permeable pavement for rainwater storage, the permeable pavement can accommodate higher rainfall intensities. The overall rainwater storage capacity (Q), calculated per 100 m, is the sum of the rainwater storage from the central irrigation channels and the porosity of the permeable pavement: $Q = Q_1 + Q_2 = 120\ m^3$.

3.1.4. Rainfall Intensity Calculation

According to the definition of rainfall intensity by the Central Weather Bureau, heavy rainfall is defined as 100 mm or more within a 3 h period. To calculate the rainfall amount for the heavy rainfall level per 100 m, the following formula can be used:

Calculating the rainwater collection area based on the full width of one side of the road, including the side ditch, permeable pavement in slow traffic lanes, permeable pavement in fast traffic lanes, and central irrigation channels. The full width of one side is 12 m.

Calculating the rainfall amount for the heavy rainfall level per 100 m (Q′) based on the full width of 12 m:

$$Q' = \text{Full width} \times 100\ \text{m} \times \text{Rainfall intensity} = 12 \times 100 \times 0.1 = 120\ m^3.$$

Based on the above, it can be concluded that the rainwater storage capacity of the permeable pavement alone is sufficient to accommodate the rainfall amount at a heavy-rainfall level. Therefore, it is evident that the permeable pavement in this project is indeed capable of effectively handling higher rainfall intensities.

3.2. Flow Analysis with Water Level Gauge

3.2.1. Field Test and Results

This plan selects 7 flow measuring stations: 3 are located on the south side of Dahua North Street (the left bank of the canal), 3 are located on the north side of Dahua North Street (the right bank of the canal), and 1 is located on the central waterway of Dahua North Street.

We use Manning's formula to estimate the theoretical flow rate of each station under different water depth conditions and the maximum water flow rate at full water level. The calculation results are detailed in Table 6. The cross-sectional view of the side ditch is detailed in Figure 12.

Table 6. List of water parameters of the station channel.

Station Number	Canal Elevation (m)				Distance (m)	Slope (m/m)	Channel Status	Manning's *n*-Value
	Up-Stream (A)	Mea-Suring (B)	Down-Stream (C)	Elevation Difference (A-C)				
L1	103.040	102.845	101.507	1.533	264.59	0.0058	Smooth	0.025
L2	102.845	101.507	100.193	2.652	391.89	0.0068	Smooth	0.025
L3	101.507	100.803	100.041	1.466	218.40	0.0067	Smooth	0.025
R1	103.040	102.748	101.842	1.198	255.26	0.0047	Smooth	0.025
R2	102.748	101.842	100.136	2.612	391.79	0.0067	Smooth	0.025
R3	101.842	100.136	99.960	1.882	240.80	0.0078	Smooth	0.025
M1	102.834	102.800	102.267	0.567	206.47	0.0027	Gravel surface	0.030

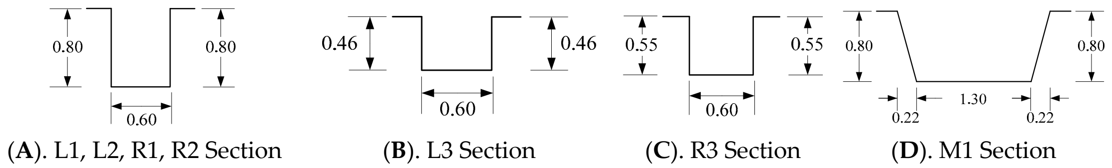


Figure 12. Sectional view of each station.

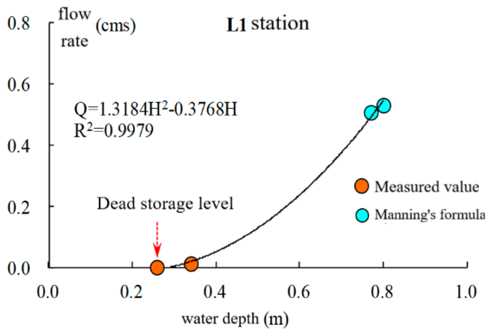
3.2.2. Establishment of Water Depth-Flow Formula

For the estimation of the bathymetric discharge rate formula, the corresponding curves of theoretical bathymetric discharge at 7 places were established by the Manning formula and in situ measurement results. According to the results of meteorological prediction, the days when heavy rain was predicted were selected for on-site measurement. However, the rainfall intensity at that time could not cause the lateral ditch to reach a high water level, so the measured data were used to estimate the discharge at the low water level. The corresponding flow of the high water level and full water level are estimated by the Manning formula, and the data are combined to estimate the water H–Q equation.

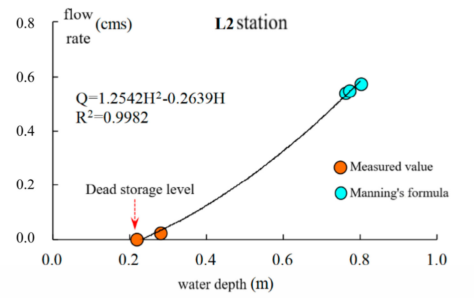
It Is hereby estimated that the water depth-discharge rate formula and its applicable restrictions are obtained by combining the theoretical method (Manning formula) with the on-site flow measurement method for each station, as shown in Table 7 and Figure 13.

Table 7. List of water depth-flow and formula at each station.

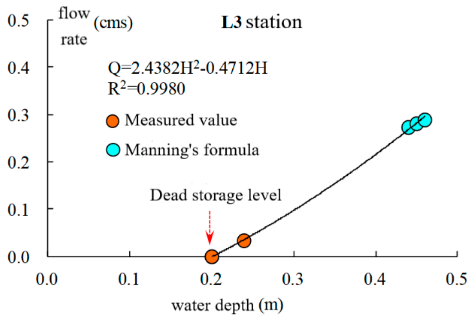
Station	Water Depth (H)—Flow Rate (Q) Formula	Coefficient of Determination	Suitable Range (m)
L1	$Q = 1.3184H^2 - 0.3768H$	$R^2 = 0.9979$	0~0.80
L2	$Q = 1.0192H^2 - 0.1997H$	$R^2 = 0.9983$	0.20~0.80
L3	$Q = 2.9422H^2 - 0.5290H$	$R^2 = 0.9983$	0.20~0.46
R1	$Q = 1.1593H^2 - 0.3092H$	$R^2 = 0.9974$	0~0.80
R2	$Q = 0.8687H^2 - 0.1516H$	$R^2 = 0.9975$	0.183~0.80
R3	$Q = 3.4755H^2 - 0.4800H$	$R^2 = 0.9994$	0.16~0.55
M1	$Q = 1.2248H^2 + 0.5055H$	$R^2 = 0.9987$	0~0.80



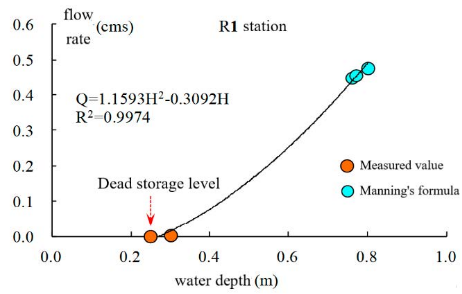
(**A**). L1 Station



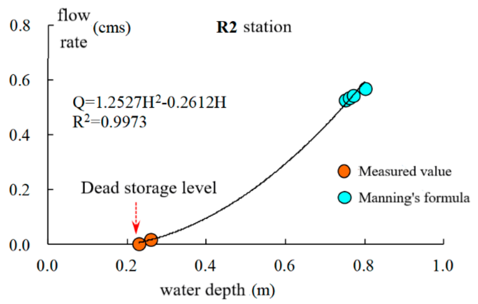
(**B**). L2 Station



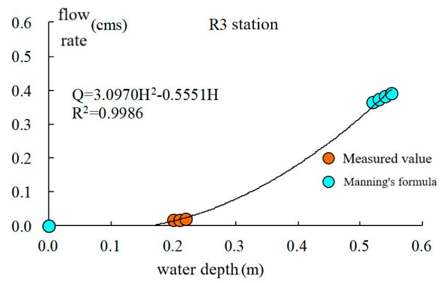
(**C**). L3 Station



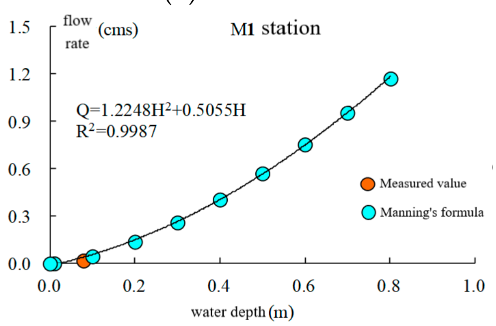
(**D**). R1 Station



(**E**). R2 Station



(**F**). R3 Station



(**G**). M1 Station

Figure 13. Comparison of estimated discharge and water depth using Manning's formula.

3.3. Outflow Analysis

In this study, the flow law formula in Section 5 is used for analysis, and the water level gauge data of the general pavement and the permeable pavement are analyzed.

We use the on-site investigation data to conduct flow analysis, derive the relationship between water level and flow, and import this calculation model into the water circulation environment system so that the system can calculate the flow of each measuring ditch,

The configuration of the water level gauge in this study shows that the upstream and downstream of the left-side groove are R1, R2, and R3, respectively.

The range from R1 to R2 collects the water flow from the permeable pavement, so the flow through R2 minus the flow through R1 is the outflow of the permeable pavement.

The range from R2 to R3 collects the water flow out of the general pavement, so the flow through R3 minus the flow through R2 is the outflow of the general pavement.

The outflow of the permeable pavement and the general pavement can be calculated from the following relationship:

1. Outflow of permeable pavement = R2 flow − R1 flow
2. Outflow of general pavement = R3 flow − R2 flow

In this study, the outflow of the pavement was analyzed on the days with daily rainfall higher than 40 mm/day in 2020, and the outflow of the permeable pavement, the outflow of the general pavement, and the rainfall were calculated by the system on the left- and right-side ditches. The results of one of the days are shown in Figure 14, and the other results are detailed in the attachment.

From the analysis results of each day, it can be seen that the outflow of the left-side ditch or the right-side ditch is greater than the outflow of the permeable pavement, and the permeable pavement can effectively reduce the flood peak.

In addition, the daily flood peak flow of the permeable pavement and the general pavement is sorted out, and the flood peak reduction amount of the permeable pavement is calculated, as shown in Table 8.

It can be seen that the permeable pavement can reduce the flood peak by 60~75% for the general pavement. In terms of the overall effect, the permeable pavement has a better water control effect than the general pavement, which is related to its water permeability and water retention capacity and is effective in low-impact development.

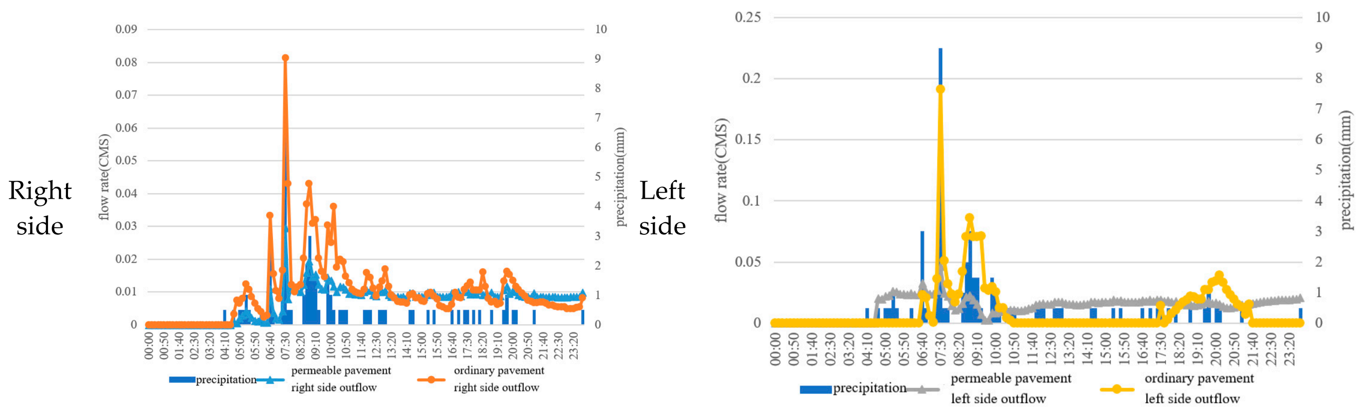


Figure 14. Flow analysis on January 26.

Table 8. Peak reduction amount of permeable pavement.

Date	Peak Flow of Permeable Pavement Right Side	Peak Flow of General Pavement Right Side	Peak Flow of Permeable Pavement Left Side	Peak Flow of General Pavement Left Side	Average Peak Reduction
26 January 2020	0.03	0.08	0.05	0.19	70%
13 March 2020	0.14	0.53	0.07	0.26	73%
18 May 2020	0.07	0.28	0.08	0.23	70%
28 May 2020	0.12	0.29	0.11	0.29	61%
2 July 2020	0.2	0.81	0.2	0.61	71%
3 August 2020	0.33	1.50	0.50	1.62	74%

4. Discussion

1. Referring to past studies on pervious pavements by domestic and foreign scholars, most of them only calculated the benefits of pervious pavement in reducing surface runoff [3–10]. However, previous scholars also mentioned the benefits of low-impact development in the past, and it is necessary to analyze the impact of rainfall on the

overall drainage system [11]. Therefore, this study uses the innovative construction method of the central ditch to combine it with a pervious pavement. By reducing the burden of the whole drainage system and calculating the actual discharge of permeable pavement and general pavement, the low-impact development benefit of permeable pavement can be analyzed more directly.

2. In this study, innovative engineering methods were used to introduce rainwater into central irrigation ditches and then into surrounding farmland for reuse. Considering that rainwater may contain harmful elements, magnetic activated carbon (MAC) and biochar will be used to remove harmful elements in reference to foreign methods [22,23] in the future. Moreover, regular water quality monitoring operations will ensure the quality of rainwater reuse.
3. According to the analysis of the data of this project, the permeable pavement can reduce the flood peak flow, but the scope of the permeable pavement in this project is not large enough, so the effect of delaying the flood peak cannot be achieved. It is suggested that permeable pavements can be used in large areas such as urban renewal or in rezoning in the future, and the effects should be monitored.

5. Conclusions

1. This study used rainy days to estimate the flow of the water level and velocity on site and established the flow law formula with Manning's formula and the regression model of subsequent water level converted flow by two methods, with R^2 values greater than 0.9. Then the actual discharge and peak discharge of the permeable pavement and the general pavement after rainfall can be calculated.
2. In this paper, an additional monitoring system is set up for the analysis of real-time return data, which can not only analyze the flood peak reduction of permeable pavement but also carry out pavement management. Monitoring data with large rainfall in 2020 are screened for the analysis of the discharge of permeable pavement and general pavement. For the general pavement, the flood peak reduction can reach 60~75%, so the permeable pavement can effectively achieve the benefit of low-impact development.
3. The biggest difference between the permeable pavement built in this paper and those studied in the past is that the permeable pavement built in this paper can store rainwater through the innovative construction method of the central irrigation ditch and permeable pavement and can temporarily store approximately 120 m^3 of rainwater based on 100 m as a unit and can accommodate heavy-rainfall intensity by using only the functions of water storage and water retention. The temporary water can be imported into farmland irrigation for reuse.
4. To summarize, by constructing a monitoring system, this paper can effectively calculate the actual discharge of permeable pavement and general pavement and analyze the length of time. In addition, through innovative construction methods, the permeable pavement in this paper can not only reduce the burden of the overall drainage system in extreme climates but also reuse rainwater. This can be used as a model for permeable pavement in the future.

Author Contributions: Validation, L.-L.H.; writing—review and editing, M.-C.H.; Data curation, Y.-S.C.; Analysis, Y.-S.C.; Writing—original draft, Y.-T.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data are not publicly available due to privacy reasons.

Conflicts of Interest: The authors declare no conflict of interest.

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