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Analysis of Thermal Pollution Reduction Efficiency of Bioretention in Stormwater Runoff under Different Rainfall Conditions

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Abstract: The thermal pollution of stormwater runoff is an important factor in the degradation of the urban water environment. Bioretention is an effective way to control the thermal pollution of stormwater runoff. To understand the influence of different rainfall conditions on the reduction of thermal pollution load of rainwater runoff from bioretention facilities and the correlation between the parameters, an experimental study was carried out by using the Beijing P&C rainfall pattern to change the rainfall parameters. By proposing innovative evaluation index parameters and analysis methods, the correlation between different parameters was quantified. The results showed that the heat pollution load reduction rate (HR) had a strong negative correlation with rainfall inflow volume (IV), rainfall duration (RD), and the service area ratio of bioretention facilities (CAR), and the correlation coefficients were −0.95, −0.73, and −0.73, respectively. HR was weakly correlated with rainfall return period (RP), rainfall temperature (RT), and air temperature (At) during the experiment, and the correlation coefficients were −0.29, 0.20, and 0.20, respectively. The delay between the peak value of heat output from the bioretention and the peak value of heat input from rainfall was about 10 min. Through the research on the change of rainwater heat entering and exiting the facility, we can master some rules of heat reduction in bioretention facilities, which will provide a reference for subsequent research on the difference between the internal heat change and bioretention temperature change.

Keywords: heat pollution; rainfall parameters; Spearman's Rank Correlation Coefficient; volume reduction; heat exchange

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1. Introduction

Urbanization construction leads to the increase of urban impervious underlying surface, which changes the thermal performance of the urban surface. The surface temperature of impervious concrete and asphalt is 19~23 °C higher than the air temperature on the premise of sufficient sunlight in summer [1]. According to the data from the National Climatic Data Center of the United States, the average outlet temperature of rainwater pipelines is 8.3 °C higher than that of cold water rivers [2,3]. The rainwater runoff formed by asphalt pavement of urban roads increases the temperature of the receiving water bodies by 5 °C and even 10~12 °C under extreme conditions [4]. The huge heat source formed by these high-temperature objects, under the scouring and convergence of rainfall–runoff, directly causes an instantaneous rise of river temperature [5], destroys the urban water environment, and produces the thermal pollution of rainwater runoff. After the summer rain, the water temperature of rivers and lakes in urban areas often rises sharply, the dissolved oxygen drops, the water quality deteriorates, and a large number of fish die [6]. Under the influence of the thermal pollution of rainwater runoff, the average temperature difference of the river after rain can reach 3.5 °C, and the maximum temperature difference can reach 7 °C. Severe temperature changes can threaten the survival of aquatic animals and plants in the river [3].

EPA has formulated relevant legal provisions, aware that the change in river temperature has threatened the living environment of aquatic organisms. The federal Energy Independence and Security Act of the United States stipulates that "all federal construction projects with a building area greater than 465 m^2 must maintain and restore the hydrological conditions after development, so that the runoff temperature, flow rate, flow and time are consistent with those before development" [7]. It is proposed to maintain and restore the runoff temperature of rainwater before site development. Previous studies have shown that the temperature of rainwater runoff after passing through the bioretention system is significantly lower than that of rainwater runoff on the roof [8]. Compared with the traditional nonpermeable pavement, the open-graded friction course (OGFC) and bioretention combined system can significantly alleviate the initial thermal effect of runoff, delaying the runoff heating time, and the biological retention zone can effectively reduce the runoff temperature of overtemperature rainwater [9]. On this basis, green infrastructure mainly based on bioretention has gradually become an effective tool for urban construction sites to restore the original hydrological conditions.

The bioretention system is mainly based on the interaction between plants, soil, and microorganisms. Through the hydrological process of natural evaporation and slow infiltration, the rainwater after infiltration and purification is added to the groundwater or into the follow-up facilities [10]. Current studies have shown that the effluent temperature of bioretention is significantly lower than the inlet temperature [11]. When the bioretention has sufficient depth (90~120 cm), it is an ideal runoff temperature control measure for cold water bodies [11,12]. An experiment in Virginia, the United States, shows that bioretention with a depth of 1.3 m can reduce the catchment temperature by 8.6 °C to 8.8 °C when the rainfall temperature is 28 °C, which shows the good cooling effect of the bioretention system [13].

Bioretention mainly reduces the outlet water temperature through the full-contact heat exchange between the runoff rainwater and the soil inside the facility. In addition, it can reduce the total heat of runoff by increasing the infiltration of rainwater runoff. For bioretention, Xu Weitong [14] studied the effects of rainfall intensity and runoff temperature on effluent temperature, and Zhang Shan [15] conducted an analysis and experiment on the reduction degree of thermal pollution of rainwater runoff from bioretention under the condition of uniform rainfall. Current research shows that the characteristics of the underlying surface, weather conditions before rainfall, rainfall intensity, and rainfall duration all affect the runoff rain temperature [16], and the smaller the service area of bioretention, the better the effect of heat pollution reduction [17]. However, the impact of different rainfall conditions on the reduction of thermal pollution of rainwater runoff from bioretention under actual rainfall patterns is not clear, and the correlation between rainfall parameters is not known. It is not clear whether the volume reduction capacity of bioretention facilities will change under different catchment temperatures; whether the heat reduction capacity of bioretention to runoff rainwater and the outlet water temperature of the facilities are affected by other factors; and whether the thermal pollution reduction capacity of bioretention can be directly evaluated based on the outlet temperature.

To further explore the relationship between the reduction efficiency of bioretention for heat pollution of rainwater runoff and rain pattern parameters, this research used the orthogonal experiment method, based on the Beijing P&C rain pattern method, to explore the impact of different rainfall temperatures, rainfall duration, rainfall return period, and catchment area on the reduction of thermal pollution of rainwater runoff from bioretention facilities. Through innovative parameter indicators and analysis methods, we found the response relationship between heat load reduction, volume reduction, and heat exchange between media of bioretention facilities in order to understand the difference between heat reduction and temperature reduction and master the variation law of peak value of facility heat discharge curve. It provides theoretical support for the application of bioretention facilities to the removal of thermal pollution from rainwater runoff, and also provides a reference for the subsequent research on the heat change and temperature change between the internal media of bioretention facilities.

2. Materials and Methods

The artificial rainfall system based on the Beijing P&C rain pattern method was used for rainfall simulation. By changing the rainfall temperature, rainfall duration, rainfall return period, and the service area of bioretention facilities, the thermal pollution control efficiency of facilities under different rainfall conditions was obtained.

2.1. Device Design

As shown in Figure 1, build 1 m × 1 m × 1.6 m (long × wide × High) stainless steel bioretention test box, the internal cylinder was a 500 mm diameter cylinder, and the filler was quartz sand with a particle size of 2~4 mm. The exterior was wrapped with aluminum foil high-density rubber plastic heat-absorbing cotton, and the insulation layer was made between the box and the internal soil column and filled with insulation asbestos. After the verification of the experimental device in the early stage, the duration of each group of experiments was 2~3 h, the internal temperature loss degree of the device was 0.11 °C/h, and the temperature loss rate accounted for about 1.04% of the inlet water temperature during the experiment.

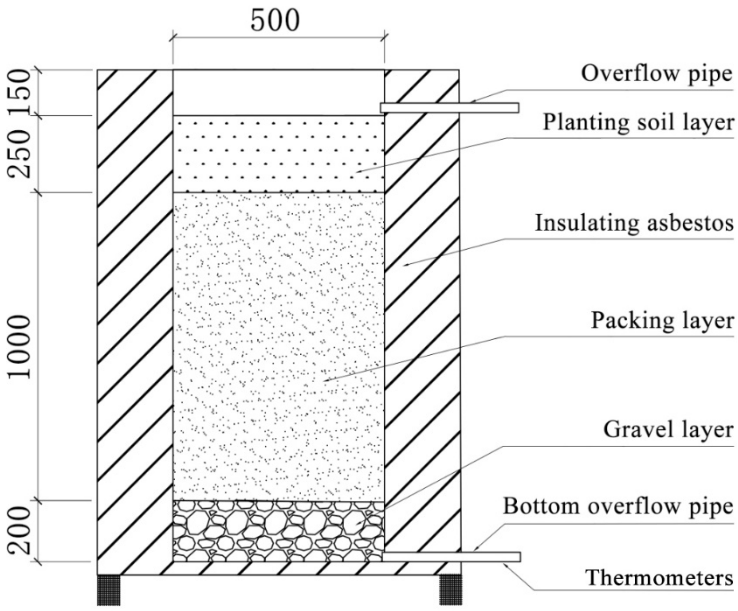

Figure 1. The experimental bioretention schematic diagram.

From top-to-bottom inside the soil column were a 150 mm water-storage layer, 250 mm planting-soil layer, 1000 mm internal-filler layer, and 200 mm bottom-gravel layer [18,19]. The soil particle size of the planting soil layer was 0.5~1 mm. Ophiopogon japonicas, which is common in northern China, was used as a plant. The particle size of the gravel layer at the bottom was 8~15 mm. DN32 seepage discharge pipes were respectively arranged in the aquifer and the gravel layer at the bottom, and thermometers were arranged at the bottom seepage discharge pipe orifice to record the outflow water temperature.

An artificial rainfall system was set above the bioretention column, including four square sprinkler heads with a side length of 150 mm and their supporting pipes, flow meters, centrifugal pumps, and water tanks. A thermostatic heater was used inside the water tank to control the artificial rainfall temperature. The rainfall interval between each experiment was 20~22 h, and 10 groups of experiments were conducted. The inflow flow was recorded by the flowmeter, the rainfall time interval was recorded by the computer, and the outflow flow of the bioretention facility was measured manually by the volumetric method.

2.2. Conceptual Design

On the premise that the rainwater runoff coefficient Ψ is certain, the rainfall volume was calculated by combining the rainfall intensity Formulas (1) and (2) of zone II in Beijing:

$$\mathrm{q} = \frac{1602(1 + 1.037\lg P)}{(t + 11.593)^{0.681}}, \quad (1)$$

$$V = 60t\Psi\mathrm{qF}, \quad (2)$$

where q is the design storm intensity [L/(s·hm^2)]; t is the rainfall duration (min); V is the total design rainfall volume (L); Ψ is the runoff coefficient; F is the catchment area (hm^2); and P is the design return period (a).

Since the shortest time for the Code for Design of Stormwater Management and Harvest Engineering to allocate rainfall patterns is 180 min, to obtain the distribution ratio of rainfall patterns under 60 min and 120 min rainfall duration, the Beijing P&C rain pattern method was selected for experimental research [20]. During the experiment, the artificial rainfall system took 5 min as a rainfall cycle, and the rainfall was calculated according to the design rainfall parameters in Formulas (1) and (2). As the biological detention facility is usually used as the source treatment facility for small and medium-sized rainfall, the rainfall return period (RP) was 1 year/2 years/5 years, the rainfall duration (RD) was 60 min and 120 min, the catchment area ratio (CAR) was 1:5 and 1:10, and the total influent volume (IV) during the experiment was recorded. As the temperature of summer rainwater runoff in Beijing is 22.8~26.6 °C [16], the experimental rainfall temperatures (RT) were selected as 22 °C, 25 °C, and 28 °C, respectively, the experiment was carried out from low to high, and the air temperature (AT) during the experiment was recorded. After the rainfall stopped, we continued to observe and record the outflow temperature and volume within one hour.

Due to a large number of experimental variables, the orthogonal experiment method was used to select representative combinations for the experiment. We used SPSS software to carry out orthogonal experimental design, added the four abovementioned parameter variables (RT/RP/CAR/RD), and set their values to obtain the orthogonal scheme design table. See Table 1 for the specific experiment contents.

Table 1. Design of the experimental scheme.

Case	Rainfall Temperature (°C)	Rainfall Return Period (Year)	Catchment Area Ratio	Rainfall Duration (min)	Influent Volume (L)
1	22	1	1:5	60	31.82
2	22	2	1:10	120	110.32
3	22	5	1:10	120	145.02
4	25	2	1:05	60	41.75
5	25	2	1:05	120	55.16
6	25	1	1:10	60	63.63
7	25	5	1:10	60	109.76
8	28	5	1:05	60	54.88
9	28	2	1:05	120	55.16
10	28	1	1:10	120	84.08

2.3. Evaluation Parameters

2.3.1. Reduction Rate of Heat Pollution Load of Rainwater Runoff

The reduction of runoff thermal pollution by green rainwater infrastructure is mainly reflected in two aspects: one is the reduction of runoff discharge volume, and the other is the reduction of outlet water temperature of the facility through heat exchange between media. The reduction rate of thermal pollution of each rainfall of the facility can be calculated according to Formulas (3) and (4):

$$EMT = \frac{\sum Qt \cdot Tt \cdot \delta t}{\sum Qt \cdot \delta t} = \frac{\int_0^{T_d} Q_t \cdot T_t \cdot dt}{\int_0^{T_d} Q_t \cdot dt}, \quad (3)$$

where EMT is the average temperature of field rainfall–runoff (°C); Q_t is the runoff generated by this rainfall (m^3/s); T_t is the runoff temperature generated by this rainfall (°C); δt is the time increment (min); and T_d is the total duration of runoff (min).

$$r = 1 - \frac{C \cdot \rho \cdot V_{out} \cdot EMT_{out}}{C \cdot \rho \cdot V_{in} \cdot EMT_{in}} \times 100\% = 1 - \frac{V_{out} \cdot EMT_{out}}{V_{in} \cdot EMT_{in}} \times 100\%, \quad (4)$$

where r is the reduction rate of heat pollution load of rainwater runoff of a single facility (%); EMT_{out} is the average temperature of the discharged runoff after passing through the bioretention facilities (°C); EMT_{in} is the average temperature of surface runoff on the underlying surface of the catchment served by the bioretention facilities (°C); V_{out} is the volume of rainwater runoff discharged by the bioretention facilities of this rainfall (m^3); V_{in} is the volume of rainwater runoff from this rainfall into the bioretention facilities (m^3); C is the specific heat capacity of water (4.2 kJ/(kg·°C)); and ρ is the density of water (1×10^3 kg/m^3).

2.3.2. Volume Control Ratio of Rainwater Runoff Heat Load

Bioretention facilities are widely used in various source volume-control measures. For the current status of heat pollution, the concept of the ratio of heat load-control rate to volume-control rate (HV control ratio) is proposed by referring to the cumulative load cumulative volume fraction curve (M (V) curve) to intuitively compare the heat pollution volume control effects of different bioretention facilities. The HV is the ratio of the heat load reduction rate η and the runoff volume reduction rate μ of this rainfall. This ratio is a dimensionless number, and its meaning is such that whenever 1% of the runoff volume can be controlled to control 1% of the heat load, the HV control ratio is 1.

Only one HV control ratio can be obtained from a single rainfall. Multiple HV control ratios of the bioretention facility can be obtained by changing the rainfall conditions to simulate multiple rainfalls, forming an HV control ratio curve. By comparing the HV control ratio data of different bioretention facilities under the same rainfall conditions, the optimal bioretention facilities for controlling the unit volume of thermal pollution of rainwater runoff under certain rainfall conditions can be obtained. Multiple groups of HV control ratio data of the same bioretention facility in a certain range of rainfall conditions are calculated, which can be used to analyze the impact of different rainfall parameters on the HV control ratio. Therefore, the HV of bioretention facilities can be expressed by Formula (5):

$$HV = \frac{\eta}{\mu} = \frac{\frac{\sum C \cdot \rho \cdot V_{i\ in} \cdot T_{i\ in} - \sum C \cdot \rho \cdot V_{i\ out} \cdot T_{i\ out}}{\sum C \cdot \rho \cdot V_{i\ in} \cdot T_{i\ in}} \times 100\%}{\frac{\sum V_{i\ in} - V_{i\ out}}{\sum V_{i\ in}} \times 100\%} = \frac{\sum V_{i\ in} \cdot T_{i\ in} - \sum V_{i\ out} \cdot T_{i\ out}}{(\sum V_{i\ in} - V_{i\ out}) \cdot \sum T_{i\ in}}, \quad (5)$$

where η is the ratio of the heat load reduction rate of this rainfall (%); μ is the runoff volume reduction rate of this rainfall (%); C is the specific heat capacity of water (4.2×10^3 J/(kg·°C)); ρ is the influent density (1×10^3 kg/m^3); V_{in} is the total volume of influent water (m^3); V_{out} is the total volume of effluent (m^3); $V_{i\ in}$ is the inflow volume per minute (m^3); $V_{i\ out}$ is the effluent volume per minute (m^3);$T_{i\ in}$ is the inlet water temperature per minute (°C); and $T_{i\ out}$ is the outlet water temperature per minute (°C).

2.3.3. Temperature Control Ratio of Rainwater Runoff Heat Load

Similar to the concept of the HV control ratio, the ratio of heat load control ratio-to-temperature control ratio (HT) is proposed for the relationship between runoff temperature controlled by bioretention facilities and heat load-reduction rate. HT is the ratio of the heat load-reduction rate η and the runoff volume reduction rate φ of this rainfall. This ratio is a dimensionless number. Its meaning is such that whenever 1% runoff temperature can be controlled to control 1% heat load, the control ratio of HT is 1.

The HT of bioretention facilities can be expressed by Formula (6):

$$\mathrm{HT} = \frac{\eta}{\varphi} = \frac{\frac{\sum C\cdot\rho\cdot V_{i\ in}\cdot T_{i\ in} - \sum C\cdot\rho\cdot V_{i\ out}\cdot T_{i\ out}}{\sum C\cdot\rho\cdot V_{i\ in}\cdot T_{i\ in}} \times 100\%}{\frac{EMT_{in} - EMT_{out}}{EMT_{in}} \times 100\%} = \frac{\left(\sum V_{i\ in}\cdot T_{i\ in} - \sum V_{i\ out}\cdot T_{i\ out}\right)EMT_{in}}{\left(EMT_{in} - EMT_{out}\right)\sum V_{i\ in}\cdot T_{i\ in}}, \quad (6)$$

where η is the ratio of the heat load reduction rate of this rainfall (%); φ is the runoff volume reduction rate of this rainfall; C is the specific heat capacity of water (4.2×10^3 J/(kg·°C)); ρ is the influent density (1×10^3 kg/m^3); $V_{i\ in}$ is the inflow volume per minute (m^3); $V_{i\ out}$ is the effluent volume per minute (m^3); $T_{i\ in}$ is the inlet water temperature per minute (°C); $T_{i\ out}$ is the outlet water temperature per minute (°C); EMT_{in} is the average temperature of surface runoff on the underlying surface of the catchment served by the bioretention facilities (°C); and EMT_{out} is the average temperature of the discharged runoff after passing through the bioretention facilities (°C).

2.4. Analytical Method

Because the rainfall parameters and their experimental results are relatively independent, Spearman's Rank Correlation Coefficient Method was selected as the correlation analysis method among the parameters in this study.

Spearman's Rank Correlation Coefficient Method is used to assign a value between −1 and 1 by measuring the degree of correlation between the two waveforms. When the assignment is positive, there is a positive correlation, and when the assignment is negative, there is a negative correlation, and the higher the absolute value assigned, the stronger the correlation.

The specific method of Spearman's Rank Correlation Coefficient is to arrange the waveform data X in ascending or descending order to obtain the sequence A and record the position of each element in the sequence X in A as r_i to obtain the rank-order column r of X. Another set of waveform data Y is arranged in the same way to obtain the rank-order column s of Y. The rank difference sequence d is obtained by successively making a difference between the elements in the sequence r and s, and the elements in the sequence d are successively brought into Spearman's Rank Correlation Coefficient Formula (7) [21]:

$$\sigma = 1 - \frac{6\sum_{i=1}^{n} d_i^2}{n(n^2-1)}, \quad (7)$$

where n is the sample size of waveform data; σ Is Spearman's rank correlation coefficient; and i is the ith sample.

To better distinguish the correlation, this paper classified the data results of Spearman's Rank Correlation Coefficient [22], as shown in Table 2.

Table 2. Correlation grading table of Spearman's coefficient.

Range	Correlation
$1 \le \lvert\sigma\rvert \le 0.5$	Strong correlation
$0.5 < \lvert\sigma\rvert \le 0.3$	Moderate correlation
$0.3 < \lvert\sigma\rvert \le 0.1$	Weak correlation
$0.1 < \lvert\sigma\rvert \le 0$	No linear relationship

3. Results and Discussion

3.1. Influence of Rainfall Pattern Parameters on the Reduction of Heat Pollution Load of Rainwater Runoff

By changing the rain pattern parameters, the experimental study on heat-pollution reduction of rainwater runoff from bioretention facilities was carried out. During the experiment, the air temperature was 16~27 °C, and the heat-reduction rate (HR), volume-reduction rate (VR), the contribution of volume reduction (CVR), and contribution of heat exchange (CHE) were obtained. See Table 3 below.

Table 3. Experimental results of rain heat-pollution-load reduction.

Case	Rainfall Temperature (°C)	Air Temperature (°C)	Influent Volume (L)	Heat Reduction Rate (%)	Volume Reduction Rate (%)	HR/VR	Contribution of Volume Reduction (%)	Contribution of Heat Exchange (%)
1	22	20	31.82	63	61	1.03	94.30	5.70
2	22	19	110.32	25	18	1.39	70.58	29.42
3	22	18	145.02	21	13	1.62	61.80	38.20
4	25	22	41.75	63	51	1.24	80.26	19.74
5	25	23	55.16	55	40	1.38	73.78	26.22
6	25	16	63.63	57	35	1.63	62.12	37.88
7	25	17	109.76	40	19	2.11	46.55	53.45
8	28	24	54.88	61	43	1.42	70.54	29.46
9	28	27	55.16	56	42	1.33	74.86	25.14
10	28	24	84.08	39	23	1.70	59.57	40.43

It can be seen from Table 3 that, based on the abovementioned rain pattern parameters, the VR of the bioretention facilities was 13~61%, which is close to the 27~76% rainfall effluent results obtained by Jones M [23] in the study on the thermal pollution of the bioretention facilities in the riparian biological reserve, so the experimental results are reliable. The reduction range of thermal pollution load of rainwater runoff was 21~63%. In addition to volume reduction, there was also heat exchange between the heat in runoff rainwater and the internal medium of bioretention facilities, so the overall reduction of thermal pollution load was slightly higher than the volume reduction rate. We created an HR and VR relation diagram, and obtained the results presented in Figure 2. With the gradual increase of VR, the rising speed of HR began to accelerate gradually. When VR was greater than 30%, the rising speed slowed down gradually. According to the data in Table 2, under the same rainfall temperature, with the increase of total rainfall volume, HR/VR also gradually increased, indicating that with the increase of rainfall volume, the contribution rate of volume reduction in heat exchange gradually decreases.

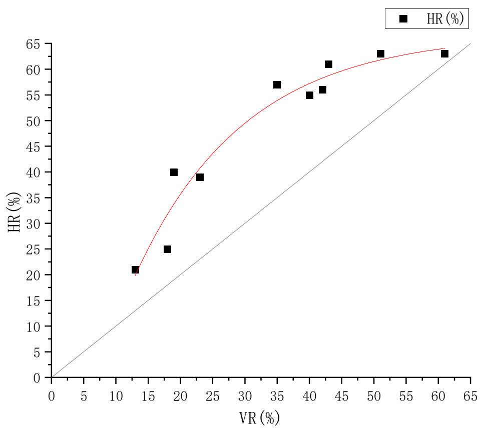

Figure 2. Experimental results of thermal pollution in bioretention facilities.

The rainfall volume is related to the rainfall return period, rainfall duration, and the catchment area of facility service. Draw Figure 3 according to the sequence of temperature from low to high and volume from small to large. It can be found that with the increase of the total volume of rainfall, the reduction rate of heat pollution decreased on the whole. Under the condition of similar rainfall volume, combined with the parameters of rainfall temperature in Table 3, it can be known that the higher the rainfall temperature, the higher the HR of facilities. The preliminary analysis of the cause of this phenomenon is that under the premise that the internal temperature of the bioretention facility is close, the RT increases, increasing the temperature difference between the rainwater and the internal medium of the facility, and enhancing heat exchange.

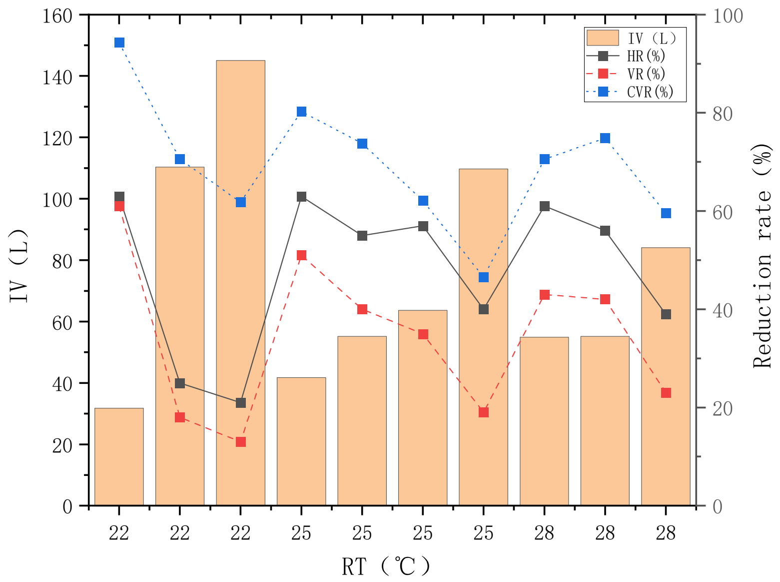

Figure 3. Experimental results of thermal pollution in bioretention facilities.

The three figures, representing the reduction rate of heat pollution, the volume reduction rate, and the volume reduction percentage, respectively, trend more closely together in Figure 3. On this basis, taking the volume reduction rate of VR as the *x*-axis, the linear fitting relationship between VR and CVR can be obtained, as shown in Figure 4 below.

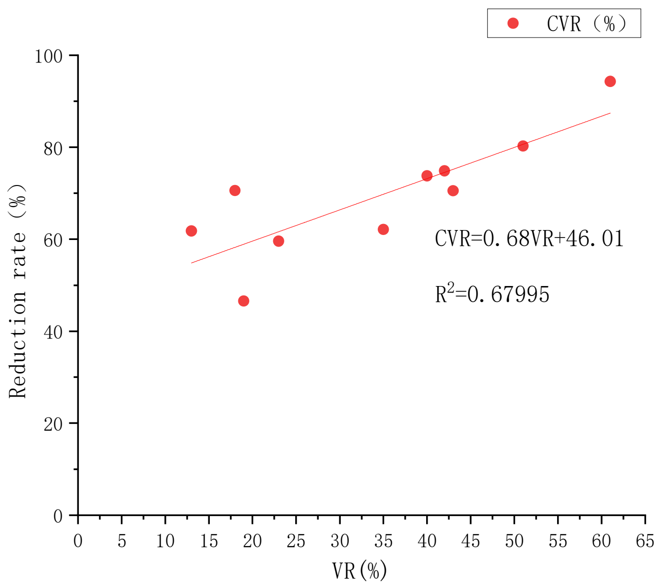

Figure 4. Linear fitting result diagram.

CVR and VR showed a linear correlation with a slope of 0.68. Therefore, with the gradual increase of VR, the growth rate of CVR slowed down, slightly lower than that of HR. As the reduction of thermal pollution is mainly caused by the volume reduction and the heat exchange inside the facility, with the increase of VR, the proportion of heat exchange (CHE) between the medium inside the bioretention facility and rainwater gradually decreased.

To further analyze the correlation between the parameters, based on the experimental results in Table 3 and the design parameters in Table 1, the Spearman's Rank Correlation Coefficient Method was used to obtain Figure 5.

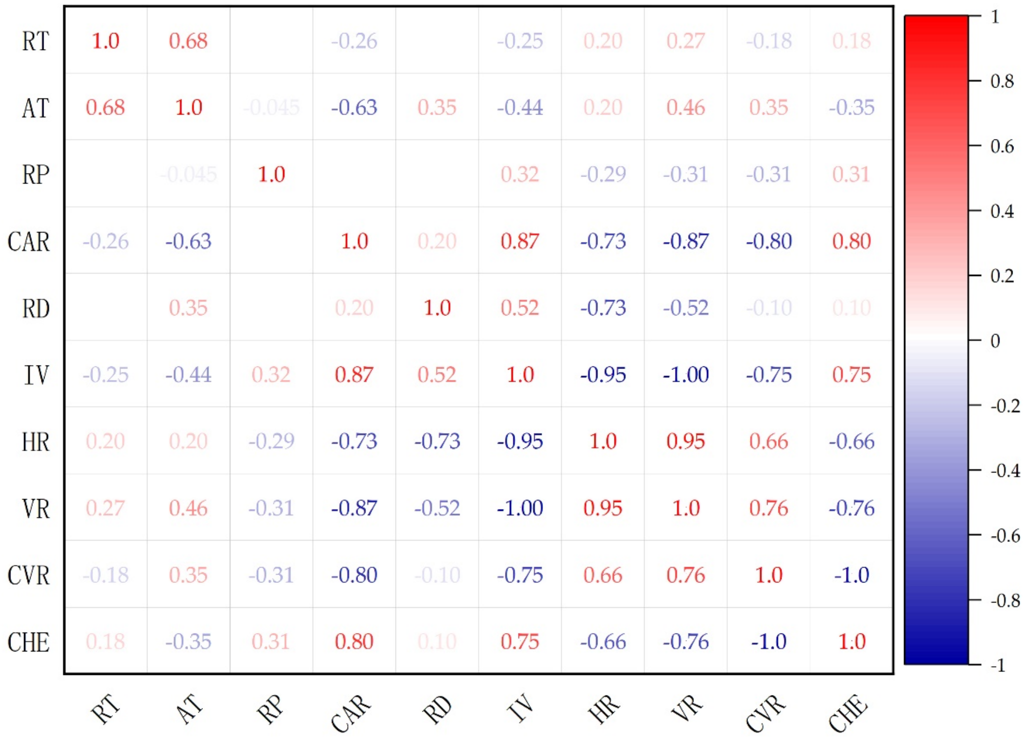

Figure 5. Spearman's Rank Correlation Coefficient results.

It can be seen from Figure 5 that HR was affected by IV, RD, and CAR, showing a strong negative correlation. Among them, the correlation coefficient between IV and HR was as high as −0.95, and RD and CAR had the same impact on HR, both of which were −0.73. This result is consistent with the existing research contents [24]. RP had a weak negative correlation with HR, which was −0.29. RT and AT had a weak positive correlation with HR, with a coefficient of 0.20. It can be found that during the experiment, the shorter the RD and the smaller the CAR, the more obvious the thermal pollution reduction effect of the bioretention facilities. However, the smaller the RP and the higher the RT were, the higher the thermal pollution reduction rate. Additionally, due to their weak positive correlation, the HR performance was still slightly improved. In the actual scene, the rainfall temperature is affected by the air temperature, and the positive correlation coefficient between AT and VR is 0.46. Therefore, in the summer when the AT is high, the thermal pollution of surface rainwater runoff will be better removed by the bioretention facilities due to the increase of VR. According to the analysis, the cause of this phenomenon is that as the air temperature rises, the surface evaporation rate increases and the water content inside the bioretention facilities decrease before rainfall. Therefore, more rainwater can be absorbed during rainfall, and the volume reduction rate is increased.

There are two ways to reduce the thermal pollution of bioretention facilities: (1) reducing the volume of rainfall; and (2) heat exchange between rainwater and internal media of bioretention facilities. It is obvious from Figure 5 that VR and HR have a strong positive correlation, and the correlation coefficient was as high as 0.95. According to the data in Table 3, the smaller the IV, the higher the VR, the higher the corresponding HR, and the larger the proportion of volume reduction in the removal of heat pollution load; when HR is low, IV is large, the heat exchange between rainwater and internal medium of bioretention facilities is more obvious, and the proportion of CHE gradually increases. Since RT also had a weak positive correlation with CHE with a coefficient of 0.15, it can be interpreted that the contribution of CHE will increase slightly with the increase in rainfall temperature. Therefore, the previous analysis suggesting that higher RT leads to higher HR is tenable.

3.2. Influence of Rain Pattern Parameters on HV and HT

During the experiment, EMT of effluent from bioretention facilities in each group was obtained, and HV and HT were obtained based on HR, as shown in Table 4 below.

Table 4. The experimental results of HV and HT.

Case	EMT (°C)	HV	HT
1	19.95	1.003	6.761
2	20.02	1.389	2.778
3	20.01	1.615	2.322
4	18.63	1.235	2.473
5	18.99	1.375	2.288
6	16.74	1.629	1.725
7	18.41	2.105	1.517
8	19.22	1.419	1.945
9	21.27	1.333	2.330
10	22.31	1.696	1.919

Based on the data in Table 4, Spearman's Rank Correlation Coefficient Formula was applied to obtain the experimental results in Figure 6.

Figure 6. The Spearman's Rank Correlation Coefficient results of HV and HT.

The average EMT of the effluent from the bioretention facilities was closely related to RD and AT during the experiment, showing a strong positive correlation, and the

Spearman's Coefficients were 0.73 and 0.60 respectively. Among them, the longer the RD, the higher the EMT of the outflow. During the experiment, the temperature was related to the experimental results. Through analysis, it can be understood that the higher the temperature, the higher the surface plant and soil temperature of the bioretention facilities, and the reduction effect of the bioretention on the rainwater temperature will be reduced. In the previous section, it was found that the higher the temperature is, the higher the VR of the bioretention facilities will be, and the better the effect of heat pollution reduction will be. Therefore, the reduction capacity of rainwater runoff heat pollution load and outlet temperature can not be generalized. HR is mainly affected by volume reduction. When the temperature is high, the contribution of volume reduction to the reduction of heat pollution load is enhanced, the heat exchange between the media is reduced, and the bottom outlet temperature of the bioretention facility will be higher than the bottom outlet temperature when the temperature is low, but the outlet volume will be reduced.

Based on the data in Table 4 and Figure 6, the following conclusions can be drawn based on removing the data with large deviation. Within the range of rainfall temperature of 22~28 °C and rainfall volume of 41.75~145.05 L, 1.235~1.696% of heat load could be controlled whenever 1% of runoff volume was controlled, and 1.517~2.778% of heat load could be controlled whenever 1% of runoff temperature was controlled. There was a strong negative correlation between HV and HT, and the coefficient was −0.87. With the increase of HV, the value of HT decreased, and both of them were affected by the catchment area. HV was also negatively correlated with AT; HT was greatly affected by RT, showing a moderate negative correlation and a correlation coefficient of −0.49. The outlet EMT of the facility also had a moderate positive impact on HT, with a coefficient of 0.39.

3.3. Analysis of the Heat-Emission Curve of Bioretention

Due to the different rainfall durations, the proportion of rainfall distribution every 5 min changed. Therefore, the occurrence time of rainfall peak in this experiment is only related to RD and has nothing to do with other rainfall parameters. On this basis, the experimental data were sorted out, and the peak time of rainfall heat (PTRH) and the peak time of outflow heat (PTOH) of 10 groups of experiments were obtained, as shown in Table 5 below.

Table 5. The design of the experimental scheme.

Case	RT (°C)	RD (min)	IV (L)	PTRH (min)	PTOH (min)
1	22	60	31.82	25	35
2	22	120	110.32	25	40
3	22	120	145.02	25	35
4	25	60	41.75	25	30
5	25	120	55.16	25	35
6	25	60	63.63	25	35
7	25	60	109.76	25	40
8	28	60	54.88	25	35
9	28	120	55.16	25	40
10	28	120	84.08	25	40

It can be seen from Table 5 that under the conditions of 60 min and 120 min rainfall duration, the peak value of the rainfall heat of the P&C rainfall pattern in Beijing occurred every at 25 min at the beginning of rainfall. It can be seen from the analysis that under the above rainfall duration, the peak rainfall happened to occur at the same time, which is when the rainfall started at 25 min, while the inflow temperature of the bioretention facility remained unchanged during the experiment, so PTRH also occurred when the experiment started for 25 min.

According to the preliminary analysis, most of the PTOH during the experiment occurred at 35 min after the rainfall. When RT and IV gradually increased, the total heat of rainfall increased, and the PTOH of bioretention facilities moved back, which occurred

40 min after the rainfall began. The occurrence time of PTOH was related to RT and IV and had no obvious relationship with rainfall duration.

Based on the abovementioned results, to understand the relationship between the heat of rainwater entering and flowing out of the facility during the process from rainfall to outflow of the bioretention facility, two typical rainfall experiments of HR were selected for research under the rainfall duration of 60 min and 120 min respectively. The selected rainfall pattern parameters are shown in Table 6 below.

Table 6. The design rainfall parameters.

RF(°C)	RP (year)	CAR	RD (min)	IV (L)	HR (%)
25	1	1:10	60	63.63	57
25	2	1:5	120	55.16	55

We calculated and counted the rainfall inflow heat and bottom outflow heat every 5 min during the experiment, and drew a cumulative curve of their percentage in the total rainfall heat and total emission heat to obtain the results shown in Figure 7.

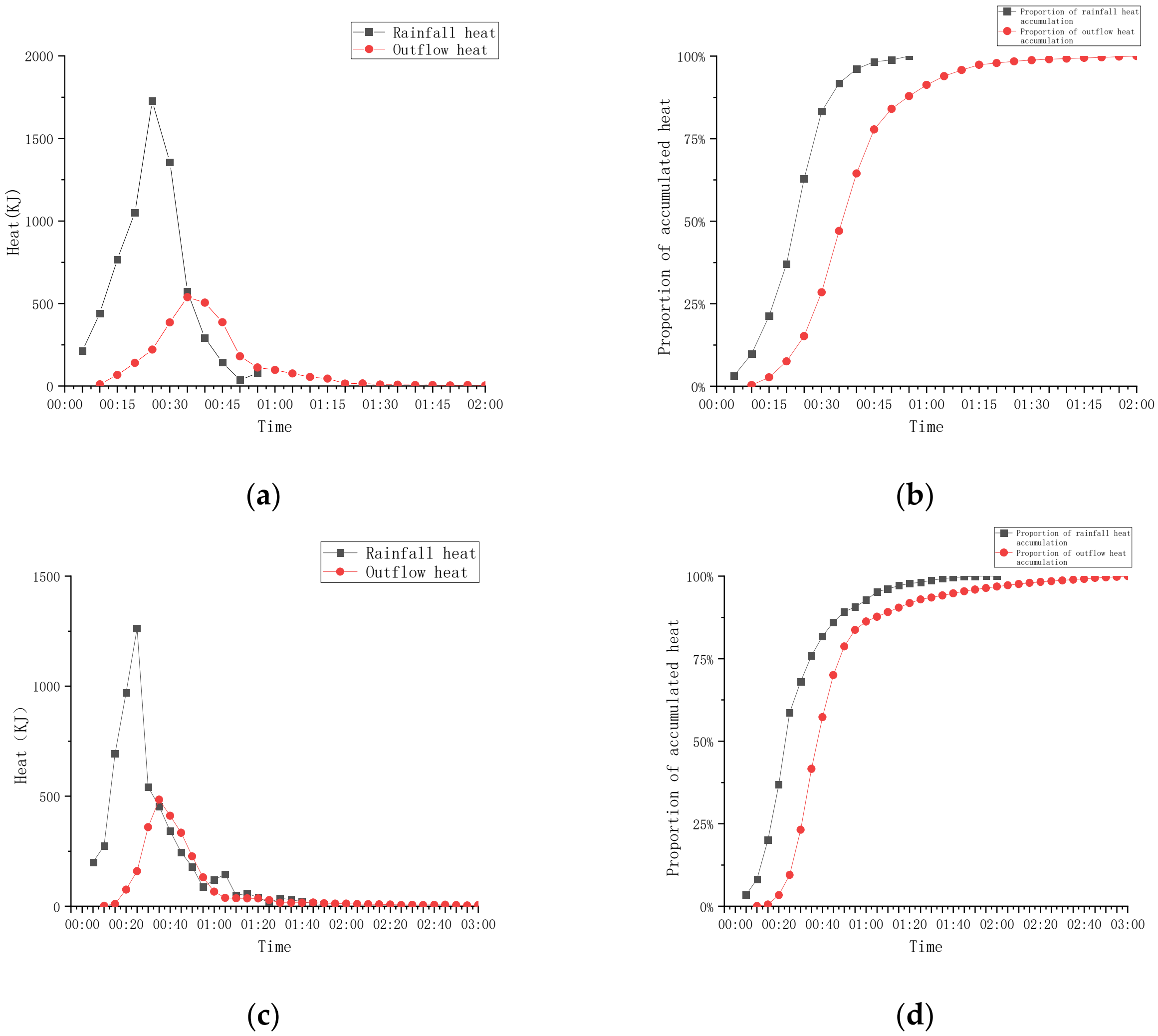

Figure 7. Experimental results of rainfall and outlet heat: (**a**) rainfall and outflow heat curve under 60 min rainfall duration; (**b**) rainfall and outflow heat accumulation curve under 60 min rainfall duration; (**c**) rainfall and outflow heat curve under 120 min rainfall duration; (**d**) rainfall and outflow heat accumulation curve under 120 min rainfall duration.

It could be found from the experimental results that under the condition of 60 min rainfall duration, the peak value of rainfall heat was 25 min at the beginning of rainfall, and the peak value of outflow heat was 35 min at the beginning of rainfall, with a delay of about 10 min. When the rainfall ended, the accumulated outflow heat at the bottom outlet accounted for 91.28% of the total outflow heat of the experiment; under the condition of 120 min rainfall duration, the peak value of rainfall heat and outflow heat was the same as that at 60 min, and the peak delay was 10 min. When the rainfall ended, the accumulated outflow heat at the bottom accounted for 96.84% of the total outflow heat of the experiment.

The experiment was ended by taking the accumulated outflow heat accounting for more than 95% of the total outflow heat as the standard. The 60 min rainfall duration experiment should be continued to observe and record for at least 10 min after the rainfall stops. At this time, the accumulated outflow heat accounted for 95.79% of the total outflow heat. In the 120 min rainfall duration experiment, when the rainfall stopped, the accumulated outflow heat accounted for more than 95% of the total outflow heat, which meets the standard, and the experimental observation could be ended.

4. Summary and Conclusions

The bioretention facilities can reduce the heat-pollution load by 21~63% and the rainfall volume by 13~61% when the RP is within 5 years; the RD was 60 min, 120 min, and the CAR was 1:5 and 1:10. The reduction of the thermal pollution load of rainwater runoff by bioretention facilities was mainly in the form of volume reduction.

HR had a strong negative correlation with IV, RD, and CAR in bioretention facilities, with correlation coefficients of −0.95, −0.73, and −0.73, respectively, and a weak negative correlation with RP of −0.29. Both RT and AT had a weak positive correlation with HR with a correlation coefficient of 0.20. The increase of AT would increase VR, and the removal effect of bioretention facilities on thermal pollution would be better. The rise of RT would increase the temperature difference between rainwater and the medium inside the bioretention, and the rise of CHE would slightly increase HR.

The heat pollution load reduction capacity of rainwater runoff was not equivalent to the outlet temperature reduction capacity, and HR was mainly affected by volume reduction. With the increase of temperature, the contribution of volume reduction to HR could be enhanced, which would reduce the heat exchange between the media, resulting in the outlet temperature at the bottom of the bioretention facility being higher than that when the temperature is low under the same conditions, but the outlet volume would be reduced more, and the total outlet heat would still be reduced.

During the experiment, when the RD was 60 min and 120 min, the peak value of rainfall heat was 25 min from the beginning of rainfall, and the peak value of outflow heat was 35 ± 5 min from the beginning of rainfall. Under the condition that the cumulative rainfall was close, RD had little effect on the arrival time of the peak rainfall and the peak heat emission of bioretention facilities, and the peak delay of both was about 10 min. The end standard of the experiment was that the accumulated outflow heat at the bottom of the bioretention accounted for more than 95% of the total outflow heat. When RD was 60 min, we continued to observe and record for at least 10 min after the rainfall stopped. For the experiment with an RD of 120 min, the end standard of the experiment was met when the rainfall stopped.

It is believed that the development of the research on thermal pollution of rainwater runoff by bioretention facilities will be gradually deepened. At present, the removal effect of bioretention facilities on thermal pollution of rainwater runoff is recognized by many experts and scholars, but the research on temperature change between different levels within bioretention facilities is still blank. How to build a temperature change model within the facilities based on experimental research will be the next research direction of bioretention facilities in the study of thermal pollution of rainwater runoff.

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References

1. Armson, D.; Stringer, P.; Ennos, A.R. The effect of tree shade and grass on surface and globe temperatures in an urban area. *Urban For. Urban Green.* **2012**, *11*, 245–255. [CrossRef]
2. Thompson, A.; Wilson, T.; Norman, J.; Gemechu, A.; Roa-Espinosa, A. Modeling the Effect of Summertime Heating on Urban Runoff Temperature[1]. *JAWRA J. Am. Water Resour. Assoc.* **2008**, *44*, 1548–1563. [CrossRef]
3. Nelson, K.C.; Palmer, M.A. Stream Temperature Surges under Urbanization and Climate Change: Data, Models, and Responses. *JAWRA J. Am. Water Resour. Assoc.* **2007**, *43*, 440–452. [CrossRef]
4. James, W.; University of Guelph; Xie, J.; Jenson, G.A. Modeling Thermal Enrichment of Streams due to Solar Heating of Local Urban Stormwater. *J. Water Manag. Model.* **1999**, *R204-08*, 139–157. [CrossRef]
5. Herb, W.R.; Janke, B.; Mohseni, O.; Stefan, H.G. Thermal pollution of streams by runoff from paved surfaces. *Hydrol. Process.* **2008**, *22*, 987–999. [CrossRef]
6. Jinqi, W.; Yuzhi, S.; Jin, H. Effects of Increasing Water Temperature on Water Properties and Aquatic Organisms: A Critical Review. *J. Hydroecology* **2020**, *41*, 100–109. (In Chinese)
7. U S Environmental Protection Agency. *Technical Guidance on Implementing the Stormwater Runoff Requirements for Federal Projects under Section 438 of the Energy Independence and Security Act of 2007*; U S Environmental Protection Agency: Washington DC, USA, 2009.
8. Yuan-lin, H. Analytical Study on the Overall Benefits of LID Stormwater System. Master's Thesis, Beijing University of Civil Engineering and Architecture, Beijing, China, 2012.
9. Xiao-jing, L.; Jun-qi, L.; Hai-jun, Q. Advance in thermal pollution of urban rainfall runoff and its mitigation measures. *J. Adv. Sci. Technol. Water Resour.* **2013**, *33*, 89–94. (In Chinese)
10. Yanwen, L. A Comparison of Road Rainwater Stagnation and Purification of the Different Bio-retention System Composed by Four Kinds of Plants. Master's Thesis, Southwest University, Chongqing, China, 2017.
11. Jones, M.P.; Hunt, W.F.; Smith, J.T. The Effect of Urban Stormwater Bmps on Runoff Temperature in Trout Sensitive Waters. In Proceedings of the 2007 ASAE Annual Meeting American Society of Agricultural and Biological Engineers, Minneapolis, MN, USA, 17–20 June 2007.
12. Jones, M.P.; Hunt, W.F. Bioretention Impact on Runoff Temperature in Trout Sensitive Waters. *J. Environ. Eng.* **2009**, *135*, 577–585. [CrossRef]
13. Long, D.L.; Dymond, R.L. Thermal Pollution Mitigation in Cold Water Stream Watersheds Using Bioretention. *JAWRA J. Am. Water Resour. Assoc.* **2013**, *50*, 977–987. [CrossRef]
14. Weitong, X.; Jianlong, W.; Yanjie, W. Immigration of thermal pollution from stormwater runoff via rain garden. *J. Water Resour. Hydropower Eng.* **2020**, *51*, 162–167. (In Chinese)
15. Shan, Z. Study of the Reduction of Urban Stormwater Runoff Thermal Pollution by Bioretention. Master's Thesis, Beijing University of Civil Engineering and Architecture, Beijing, China, 2020.
16. Li, J.; Gong, Y.; Li, X.; Yin, D.; Shi, H. Urban stormwater runoff thermal characteristics and mitigation effect of low impact development measures. *J. Water Clim. Chang.* **2018**, *10*, 53–62. [CrossRef]
17. Li, H.; Davis, A.P. Water Quality Improvement through Reductions of Pollutant Loads Using Bioretention. *J. Environ. Eng.* **2009**, *135*, 567–576. [CrossRef]
18. Sabouri, F.; Gharabaghi, B.; Mahboubi, A.; McBean, E. Impervious surfaces and sewer pipe effects on stormwater runoff temperature. *J. Hydrol.* **2013**, *502*, 10–17. [CrossRef]
19. Hunt, W.F.; Davis, A.; Traver, R. Meeting Hydrologic and Water Quality Goals through Targeted Bioretention Design. *J. Environ. Eng.* **2012**, *138*, 698–707. [CrossRef]
20. Jing-lei, M. Design Storm Pattern Analysis in the City of Beijing. Master's Thesis, Lanzhou Jiaotong University, Lanzhou, China, 2011.
21. Ke, J.; Zhe, Y.; Chao, W. Pilot Protection Based on Spearman Rank Correlation Coefficient for Transmission Line Connected to Renewable Energy Source. *J. Autom. Electr. Power Syst.* **2020**, *44*, 103–111. (In Chinese)
22. Cohen, J. *Statistical Power Analysis for the Behavioral Sciences*, 2nd ed.; Routledge: New York, NY, USA, 1988; p. 334.

23. Jones, M.P.; Hunt, W.F. The Effect of Bioretention on Runoff Temperature in Trout Sensitive Waters. In Proceedings of the American Society of Agricultural and Biological Engineers, Providence, RI, USA, 29 June–2 July 2008. [CrossRef]
24. Junqi, L.; Mengqi, S.; Xiaojing, L. Experimental Study on Thermal Pollution Control of Stormwater Runoff by Bioretention. *J. Water Resour. Prot.* **2022**, *38*, 6–12. (In Chinese)