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Research Article

Adaptive Rainwater Management on Coral Islands: Multi-Method Integrated Rapid Optimization of Bioretention Systems

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Abstract: Although tropical coral islands receive abundant annual precipitation, the heavy rainfall and the high porosity of coral sand lead to rapid rainwater loss, posing a severe challenge to water use, soil water retention, and plant growth. Traditional bioretention systems are not suitable for these unique conditions, and there is still no effective adaptive framework for designing specific coral island bioretention systems. This study provides an efficient multi-method framework for the bioretention systems on coral islands. A bioretention system with engineering feasibility is constructed by using coral sand as the main substrate and combining it with common fillers. Then, the Analytic Hierarchy Process (AHP) is adopted to determine the optimal combination. Subsequently, the model was combined with the response surface method to compare the performance of the bioretention systems under different design parameters and determine the optimal setting. Finally, by simulating the actual rainfall conditions on the island, the performance of the optimized bioretention systems during the dry and rainy seasons was evaluated. The results show that under heavy rainfall conditions, the reduction rate of the total runoff volume of the optimized system is 67.7%. It is superior to pure coral sand in rainwater interception, and the total suspended solids in the effluent are less than 4 mg/L. These findings provide valuable insights into the development of bioretention systems on coral islands and propose a methodological framework to assist in the rapid establishment of such systems in other areas.

Key words: Bioretention system; Coral islands; DRAINMOD; Response surface; Optimization.

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1. Introduction

Coral islands consist of calcium carbonate sediments from reef-building organisms' skeletons and shells, and are widely distributed globally (**Fig. S1**). Millions rely on them for fisheries, tourism, mineral exploration, coastal hazard protection, and other food security-related ecosystem services [1]. Coral islands contribute an estimated US$2.4 trillion annually, accounting for 2.2% of global ecosystem services [2]. These marine ecosystems are highly productive and biodiverse globally, and they flourish in a certain spectrum of biophysical, oceanic, and climatic circumstances [3].

Most coral islands are located offshore and often face significant challenges in freshwater availability [4,5]. Currently, rainwater collection, desalination, sewage reclamation, and boat transportation are still the primary methods used to ensure freshwater security in these coral islands [6,7]. Given these challenges, rainwater, as the primary freshwater source on these islands, offers economic, convenient, and sustainable benefits, highlighting the importance of research on rainwater reuse [8,9]. However, the primary soil component of the coral islands is coral sand, which has high porosity and a high permeability coefficient [10,11]. These traits limit rainwater collection by causing rapid infiltration, seriously depleting freshwater resources. Furthermore, the competition between water for domestic use and water for ecological purposes is exacerbated by the fact that coral sands' poor water-holding qualities mean that there is frequently insufficient water in them after rainfall to support normal plant growth. Thus, there are still certain obstacles and problems with studies on water storage and stagnation in coral islands.

Bioretention systems —a key Low Impact Development (LID) element —provide benefits including runoff reduction, rainwater retention, water quality improvement, and landscape enhancement, which match coral islands' needs [12,13]. In inland areas, Bioretention systems generally exhibit good performance in treating conventional stormwater runoff pollutants [14,15]. Various amendments were incorporated into the bioretention systems, trying to facilitate different biochemical processes [16]. Kong et al. developed a pyrite-based bioretention system that demonstrated high efficiency and stability in controlling urban runoff [17]. Greksa et al. incorporated organic composts into the media mixtures to promote a suitable environment for plant development [18]. Various fillers have also performed well in bioretention systems for urban

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stormwater runoff treatment processes [19,20]. However, the unique conditions of coral islands, characterized by constraints on the use of fill soil, low soil water-holding capacity, low-pollutant rainwater, and challenging vegetation growth conditions, render traditional mainland bioretention systems unsuitable for direct application.

Overall, through extensive research and fieldwork, the application of bioretention systems on the coral islands examined mainly faces the following three major specificities:

1) Meet the balance of rainwater retention and infiltration

The main soil component of coral islands is coral sand, which has good permeability properties to meet the infiltration needs of bioretention systems, but the excessively high permeability coefficient also makes the pure coral sand bioretention systems show poor rainwater retention capacity. It is crucial to figure out how to balance infiltration and retention in bioretention systems.

2) Limitations of media usage

Unlike inland areas (which use various soils), coral islands' predominant soil is coral sand. To ensure the practical feasibility of engineering projects, it is essential that coral sand serves as the primary filler material in bioretention systems, thereby maximizing cost-effectiveness. However, the physicochemical characteristics of coral sand differ significantly from those of conventional inland soil [21,22]. How to use coral sand as the core component of a bioretention system that works for coral islands is also a challenge.

3) Specificity of water quality

Inland stormwater runoff is primarily contaminated by heavy metals, TP, TN, COD, and solid suspended particles [23,24]. Dissimilar to inland areas, coral islands are located far from inland, have fewer human activities and pollution sources, and are more likely to form the primary pollutants of solid suspended solids as rainwater runoff during short-term periods of intense rainfall **(Table S1)**. It is practically significant to develop bioretention systems adapted to the specificities of island water quality.

Therefore, the development of bioretention systems applicable to coral islands to improve the utilization of rainwater resources on islands, slow down the rate of decline in water content of coral sand soils, and control the problem of surface source pollution are of practical significance to improve the ecology of islands. However, research on bioretention systems is mainly based on experiments and on-site monitoring, while coral islands are far away from the mainland, and the conduct of various types of experiments is affected by factors such as space and materials, which makes it unsuitable for carrying out large-scale research. Model simulation is frequently required in order to optimize the design of the bioretention system and forecast the operational results [25]. As a commonly used model for bioretention systems, DRAINMOD is a site-independent, dependable, affordable, and easy-to-use tool that can forecast operational outcomes and optimize design parameters [26-28]. Therefore, this study developed a coral island-oriented bioretention system using coral sand as a substrate by hierarchical analysis method based on the background conditions such as rainfall conditions, hydrological characteristics, and geological characteristics of the coral island. On this basis, the design parameters of the bioretention system were optimized by using the DRAINMOD model combined with the response surface test [29], so as to achieve the purposes of rainwater management in bioretention system. Finally, the final experiments simulated actual rainfall conditions on the islands, evaluating the performance of the optimized bioretention facility during both dry and rainy seasons.

This study can be mainly divided into the following parts: 1) the study of filler selection and proportioning of bioretention system. 2) the optimization of the design parameters of the bioretention system. 3) the actual operation of the bioretention system under the optimal design scheme.

2. Material and methods

Fig. 1 shows the technical framework for developing adaptive bioretention systems. This approach has four components: 1) Selection and optimization of media layers; 2) Development and analysis of the DRAINMOD model; 3) Optimization of operating parameters using Response Surface Methodology; 4) Validation of the operation of the optimal combination of bioretention systems.

2.1. Establishment of bioretention systems

The bioretention system's main body is an acrylic tube (125 cm tall, 200 mm diameter). Its internal structure—from top to bottom—includes a ponding zone, protective layer, soil layer, filler layer, gravel layer, and support layer **(Fig. 2)**. An overflow port was added to the system's side at the ponding zone top; a 400 mm elevated outflow port was set at the gravel layer bottom to create an internal storage area, and a drain port at the bottom. A permeable geotextile, 200 mm in diameter, was placed at the bottom of the soil, filler, and gravel layers to prevent the loss and mixing of different media layers. The bioretention system was filled from bottom to top via wet filling, with each 3–4 cm layer compacted by a wooden mallet. Post-filling, the system was rinsed with tap water, and tests began once effluent quality stabilized

2.2. Test water

The test water was manually prepared, and rainfall was simulated using a combination of peristaltic pumps and sprinkler heads. Based on collected rainfall data **(Table S1)**, this study selected three typical rainfall intensities (10, 40, 80 mm/h) to simulate coral island rainfall events. The simulated rainfall volume was calculated as follows:

$$Q = \varphi q F \quad (1)$$

In terms of water quality, we investigated that the main source of pollution in coral islands is TSS with concentrations ranging from 50 mg/L to 450 mg/L, and the concentrations of typical pollutants COD_{Mn}, NH_4^+-N, and TN are relatively low（**Table S2**）. Importantly, coral island runoff TSS is dominated by calcium carbonate-rich coral sand debris—an inert material with low chemical adsorption activity. For such particulates, bioretention systems remove TSS mainly via physical interception. To ensure the simulated TSS matches the actual runoff characteristics of coral islands, we first compared the properties of candidate materials with field-collected runoff samples: reference to the runoff samples collected from Island during the 2023 rainy season showed that the TSS in coral island runoff is mainly composed of coral sand debris, with a particle size range of 0.05–1 mm and calcium carbonate con-

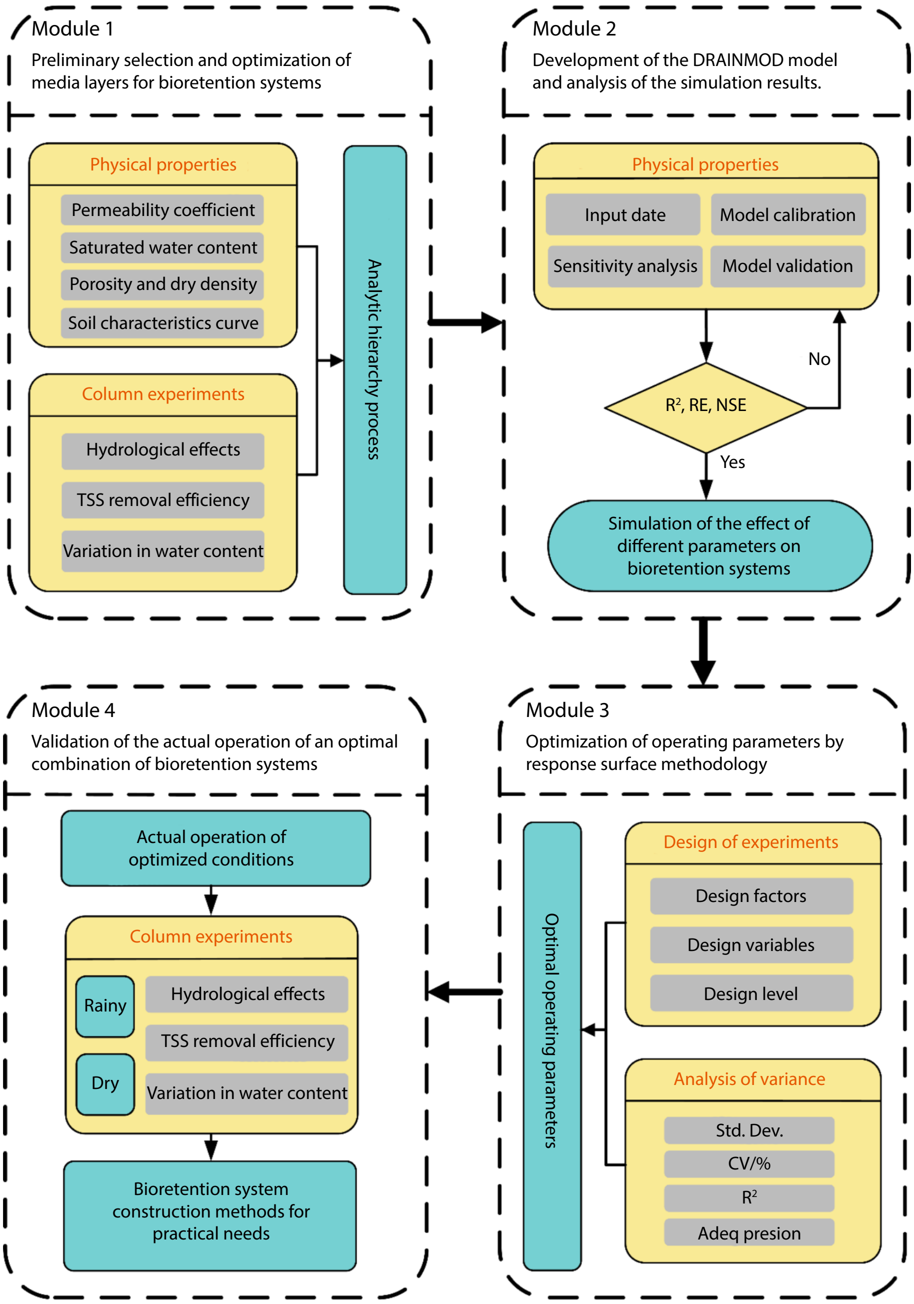

Fig. 1. An overview of the optimization methods framework

tent > 80%. Although the selected red soil (sieved to < 1 mm; main components: 65% SiO_2, 15% Al_2O_3 via XRF) differs chemically from coral sand, its particle size distribution (0.02–1 mm) and sedimentation behavior match coral sand debris—satisfying the need to simulate suspended solids filtration in runoff. Additionally, the TSS concentration of 250 mg/L used in the test was determined based on the measured TSS range (50–450 mg/L) of coral island stormwater runoff in **Table S2**, and the median value was selected to cover most conventional rainfall scenarios. Thus, the study utilized laterite with a particle size of less than 1 mm, mixed with rainwater at a TSS concentration of 250 mg/L, to simulate the normal water quality of runoff from coral islands.

2.3. Evaluation indicators and measurement methods

To evaluate the characteristics of bioretention system, the key indicators for bioretention system include: hydrological effects, total suspended solids removal rate (R_{TSS}), and soil layer water content reduction rate (R_w). Hydrological effect indicators include: total runoff reduction rate (*TRRR*) and total runoff peak reduction rate (R_p). During simulated rainfall, outflow from the system's outflow and overflow ports was timed, and volumes were recorded with a measuring cylinder every 2 minutes. The calculation equations are as follows:

$$TRRR = \frac{Q_{inf} - Q_{eff}}{Q_{inf}} \tag{2}$$

$$R_p = \frac{Q_{infpeak} - Q_{effpeak}}{Q_{infpeak}} \tag{3}$$

where Q_{inf} (mL) and Q_{eff} (mL) are total inlet flow and total outlet flow, $Q_{infpeak}$ (mL) and $Q_{effpeak}$ (mL) are peak inlet and peak outlet flows.

The TSS concentration was determined using the weight

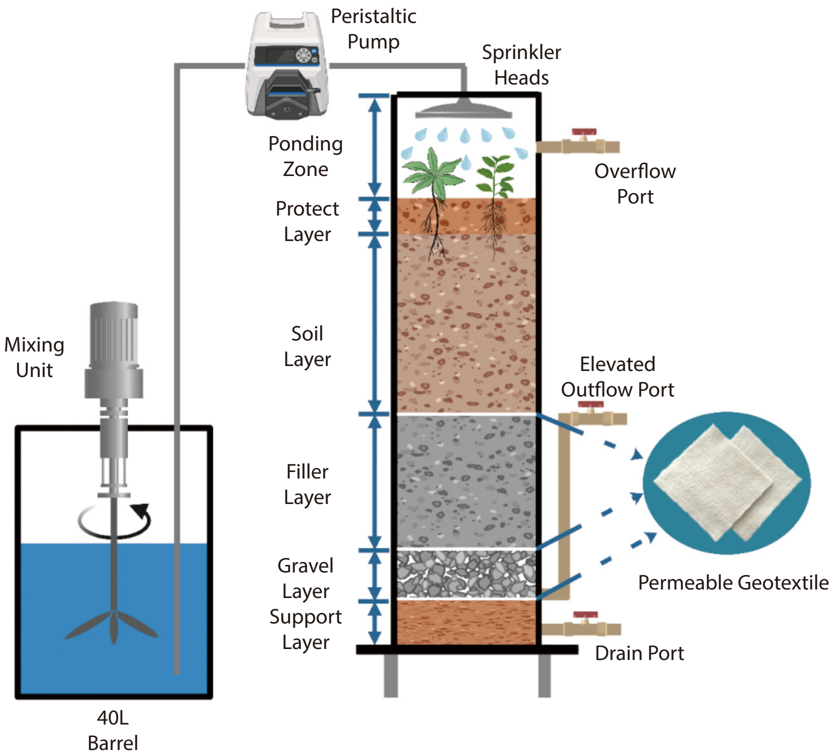

Fig. 2. Schematic of the bioretention system and instruments

method, R_{TSS} was calculated by the following formula:

$$R_{\mathrm{TSS}} = \frac{TSS_{inf} - TSS_{eff}}{TSS_{inf}} \tag{4}$$

where SS_{inf} (mL) and SS_{eff} (mL) represent total inlet and outlet suspended solids.

R_w was measured using a portable water content tester (VICOMETERVM210S), and the rate of decrease in water content was calculated by the **Eqa.5**.

$$R_w = \frac{C - C'}{24} \tag{5}$$

where C is the saturated water content, and C′ is saturated water content after 24 hours.

2.4. Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) is a widely used multi-objective decision-making method that decomposes complex problems into three levels: objectives, criteria, and plans [30,31]. The relative importance of lower-level factors is evaluated by experts, and weighted rankings are made based on their significance, allowing for quantitative analysis and comparison to select the best choice at the target level. This method simplifies complex problems and calculations. As a model that combines quantitative and qualitative analysis, it has high validity and reliability and wide applicability. It generally includes four parts: determining the target and evaluation factors, constructing the judgment matrix, calculating the matrix, and consistency testing. [32,33].

To screen for the optimal performance of soil and fill layers, this study takes the optimal combination of soil and fill layers as the target level, the total runoff control rate, runoff delay time, peak stagnation reduction rate, peak stagnation time, TSS reduction rate, soil moisture content reduction rate and total cost as the criterion levels, and seven different configurations as the program levels. The data was analyzed using the AHP **(section 3.1.3).**

2.5. DRAINMOD model

This study employed a drainage model to simulate the hydrological effects of bioretention systems under different design conditions. The principle of this model is based on two main concepts of water balance [34]:

① Soil cross-section water balance:

$$\Delta V_a = D + ET + DS - I \tag{6}$$

where ΔV_a (cm) represents the change in water volume in the soil cross-section, D (cm) indicates subsurface drainage, ET (cm) denotes the evapotranspiration, DS (cm) represents lateral drainage and deep percolation, and I (cm) indicates infiltration from the soil surface.

② Soil surface water balance:

$$P = I + \Delta S + RO \tag{7}$$

where P (cm) is the precipitation, ΔS (cm) is the change in soil surface water storage, and RO (cm) is the surface runoff.

The hydrologic module of the DRAINMOD model is used in this study to simulate bioretention systems. The input parameters for DRAINMOD include the catchment area ratio (R), aquifer height (H_1), drain spacing (L), effective drain radius (R_e), drainage coefficient (k), internal storage height (H_2), saturated hydraulic conductivity of the restricted drainage layer (K_R), soil layer depth (D_1), filler layer depth (D_2), and permeability coefficient (K). The main input files required for the model include catchment area files, weather files, soil files and design parameters. The catchment area file simulates the production of water tanks within the catchment area and can be created using the drainage mod. The weather file includes daily maximum and minimum temperatures for simulating potential evapotranspiration (**https://rp5.ru**). Considering the high calcium carbonate content of coral sand (which alters its pore structure and hydraulic behavior), the default soil hydraulic parameters in the drainage mod were adjusted based on laboratory measurements. The soil moisture characteristic curves required for the soil file are shown in **Fig. S2.**

2.6. Response Surface Methodology

Response Surface Method (RSM) is an integrated experimental design and mathematical modeling optimization technique. It offers advantages such as fewer tests, shorter test durations, higher accuracy, precise regression equations, powerful predictive performance, and the ability to analyze the interactions among multiple factors. RSM has been applied in multiple fields, and the experimental results have been improved [35,36]. Researchers have successfully utilized response surface analysis to optimize the design parameters of bioretention systems [29,37]. This study combines the RSM method, response surface method and DRAINMOD model to optimize the design parameters of the bioretention systems on coral islands.

Based on the experimental data of the drainage model bioretention system, its design was optimized under baseline rainfall conditions. These conditions include rainfall intensity of 40 mm/h, duration of 1 hour, pre-drying time (ADD) of 1 day, and the use of Response Surface Analysis (RSA) and Box-Behnken Design (BBD) methods in Design-Expert software.

3. Results and discussion

3.1. Optimization of media layers for bioretention system

3.1.1. Primary selection of media materials

As an important component of the media layer, the materials play a crucial role in the performance of bioretention systems by influencing the permeation capacity and pollutant removal efficiency. For bioretention systems located on coral islands, the media material must mainly consist of coral sand to ensure actual relevance. However, when pure coral sand is used as the medium layer, its permeability is too high, making the system unable to meet the storage and detention requirements. Therefore, in this study, several common materials (biochar, coconut charcoal, vermiculite, peat) were mixed together with coral sand. The physicochemical properties of the mixed medium, such as saturated water content, average porosity, dry density and permeability coefficient, were comparatively investigated (**Fig. 3**) to identify a suitable batch of fillers that may meet the requirements for the bioretention system's filler layer for subsequent column experiments **(Section 3.1.2)**.

Specifically, the media layers of bioretention system mainly include the soil layer and filler layer [38]. The mixing of materials is conducted to enhance each layer based on its distinct functions. The soil layer must exhibit good infiltration performance to facilitate the rapid infiltration of rainwater runoff, thereby reducing runoff, while also possessing sufficient water retention capacity to support normal plant growth. As illustrated in **Fig. 3a**, the infiltration coefficient (A) of coral sand is as high as 1012.8 mm/h. However, this high permeability coefficient also leads to poor water retention capacity, which limits its ability to provide sufficient water for plant growth and thus affects plant health. Among the 7 groups of mixed media, the composite permeability coefficients of the mixed fillers in groups E and F were 750.9 mm/h and 810.4 mm/h respectively, indicating that the composite permeability was moderate. In addition, both E and F exhibit good saturated water content and porosity (**Fig. 3b**). Consequently, fillers E and F were selected as the soil layer for the subsequent column experiments. Regarding the filler layer, its primary role is to remove pollutants while providing some water retention; however, the water retention requirement is not as critical as that of the soil layer. Given that the primary pollutants in stormwater runoff from coral islands are solid suspended solids (**Table S1**), biochar, vermiculite, and coconut coir, which are effective in removing suspended solids, were chosen as blended fillers. The three selected fillers with moderate permeability coefficients, B, H, and G, were designated as materials for the filler layer.

3.1.2. Performance of different media layers in column experiments

To examine the effectiveness of different media layers of bioretention systems in controlling runoff, water-holding, and TSS, a series of pilot-scale column experiments was designed. The bioretention with different media compositions were categorized into three series, A, B, and C, numbered as A1, A2, A3, B1, B2, B3, and C (**Fig. S3**), the detailed media composition is

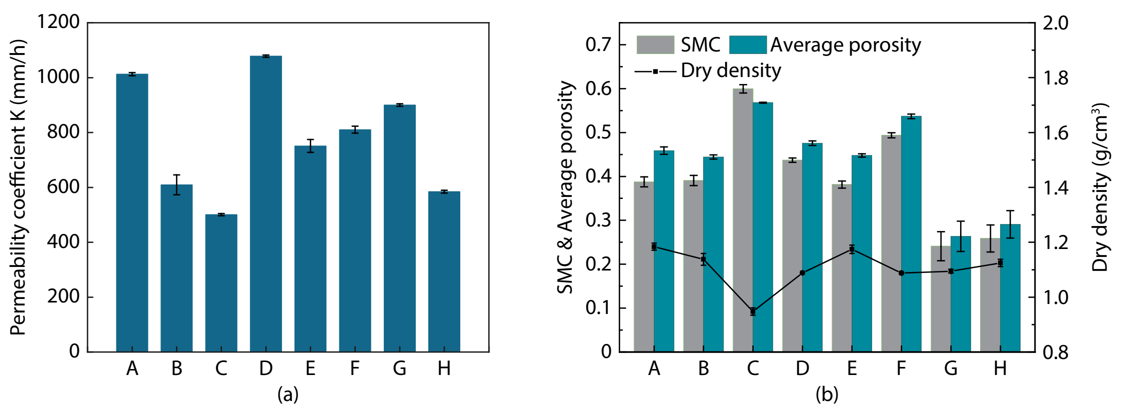

Fig. 3. The physicochemical properties of mixed media

(A-Coral sand, B-Coral sand: Biochar=9:1, C-Coral sand: Coconut bran=19:1, D-Coral sand: Vermiculite=19:1, E-Coral sand: Red soil=9:1, F-Coral sand: Peat: Red soil=15:4:1, G-Coral sand: Coconut bran=9:1, H-Coral sand: Vermiculite=9:1)

Table 1. Bioretention systems' media composition and properties.

Reactor	Covering layer	Soil layer	Filler layer	Supporting layer
A1	Horsetail	75% Coral sand+20% Peat+5% Red soil	90% Coral sand+ 10%Vermiculite	Gravel
A2	Horsetail	75% Coral sand+20% Peat+5% Red soil	90% Coral sand+10% Biochar	Gravel
A3	Horsetail	75% Coral sand+20% Peat+5% Red soil	90% Coral sand+ 10% Coconut bran	Gravel
B1	Horsetail	90% Coral sand+10% Red soil	90% Coral sand+10% Vermiculite	Gravel
B2	Horsetail	90% Coral sand+10% Red soil	90% Coral sand+10% Biochar	Gravel
B3	Horsetail	90% Coral sand+10% Red soil	90% Coral sand+10% Coconut bran	Gravel
C	Horsetail	Coral sand	Coral sand	Gravel

listed in **Table 1**. Based on the meteorological data statistics of coral island **(Table S2)**, the rainfall intensities used in the experiment were finalized to be 10 mm/h, 40 mm/h, and 80 mm/h; rainfall durations of 0.5 h, 1 h, and 1.5 h, and ADD of 1 d, 3 d and 7 d. Detailed analysis of the series of column experiments can be seen in **Text S1**.

3.1.3. Optimal strategy based on Analytic Hierarchy Process

Previous experiments showed seven media-filled columns performed differently across treatment indices. To identify the optimal soil and filler layers, we analyzed the data using AHP. A hierarchical model was established with the following evaluation criteria: total runoff control rate (P1), runoff delay time (P2), peak flow control rate (P3), peak lag time (P4), total suspended solids (TSS) reduction rate (P5), reduction rate of water content in the soil layer (P6), and total cost (P7) **(Fig. 4)**.

The weights of the seven evaluation criteria (P1–P7) were determined via expert scoring. Five experts with over 10 years of experience in coral island hydrology and low-impact development (LID) systems were invited to compare the relative importance of each criterion pairwise, based on coral islands' core needs. A pairwise comparison matrix was constructed, followed by a consistency test of the pairwise comparison judgment matrix (**Table S4**). The maximum eigenvalue of the matrix was calculated to be 7.272, with a consistency index (CI) value of 0.045, a random index (RI) value of 1.341, and a consistency ratio (CR) value of 0.034, indicating that the consistency of the judgment matrix is acceptable (**Text S2**).

The experimental data under strong rainfall conditions (rainfall intensity of 80 mm/h, rainfall duration of 1 hour, and antecedent dry days (ADD) of 1 day) were used as simulation scenarios to calculate the evaluation index values for devices A1–A3, B1–B3, and C. To optimize the hierarchical analysis, the rate of decrease in water content in the soil layer was converted to the amount of water retained in the soil layer, and the total cost was expressed in terms of remaining funds. The standardized evaluation index values are presented in **Table S5**.

The normalized evaluation metric values were multiplied by their corresponding weights to obtain the final ratings for each device, as illustrated in the radar plot shown in **Fig. 5**. The findings indicate that, aside from the evident drawbacks associated with devices A3 and B3, the overall effectiveness of the devices in controlling precipitation runoff remains largely unchanged. Currently, the critical factor determining the effectiveness of the devices is the rate at which water content declines in the soil layer, with the B series demonstrating the greatest improvement. Among all tested devices, Device B1 ranked first with a rating of 0.164. The key reason for its superior overall performance over other systems lies in the balance of its performance across various aspects, which is specifically reflected in three aspects: First, the soil layer of this device adopts a ratio of "coral sand + red soil (9:1)", which significantly improves water retention performance — at a depth of 10 cm, its water retention rate reaches 21.6%, while the water retention rate of pure coral sand at the same depth is only 14.0%; Second, the filler layer uses "coral sand + vermiculite (9:1)", which can ensure that the total suspended solids (TSS) removal rate is stably higher than 98%; Third, it has a significant advantage in cost control, being 15% lower than similar systems that use peat.

Ranking second is Device C with a rating of 0.154; followed by Devices B2, A2, and B3 in sequence, while Device A3 has the lowest rating among all tested objects. In summary, from the perspective of overall performance, the bioretention system with "coral sand + red soil" as the soil layer and "coral

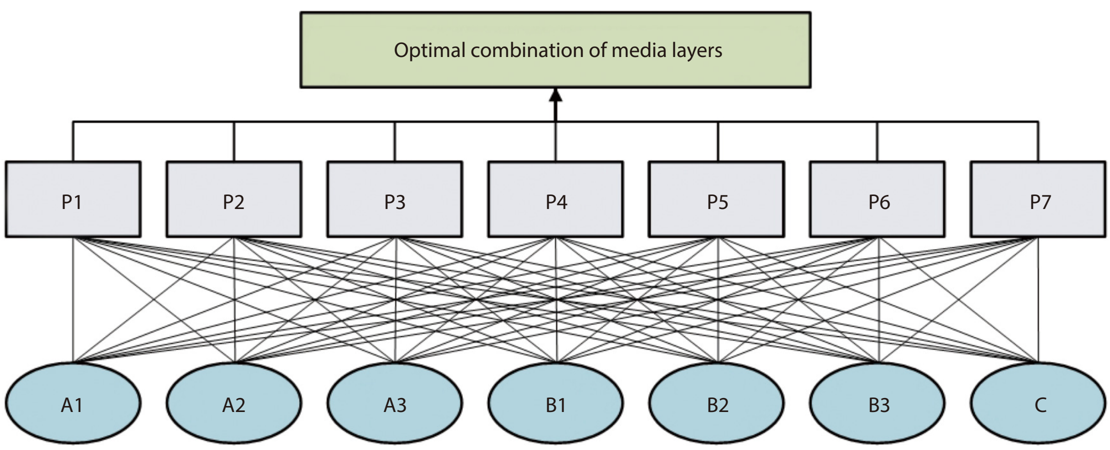

Fig. 4. Hierarchical model for filler selection

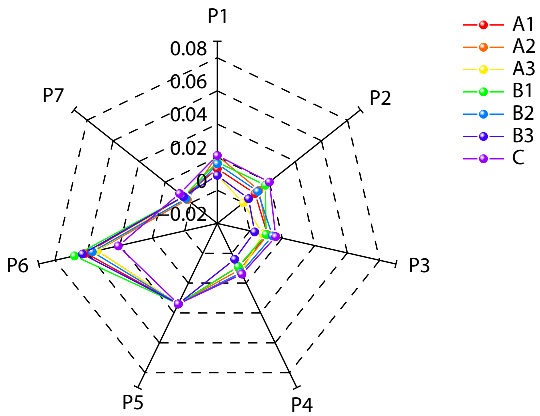

Fig. 5. Analytic Hierarchy Process scoring radar chart

sand + vermiculite" as the filler layer is the optimal-performing solution in this study.

3.2. Optimization of design parameters for bioretention system

3.2.1. Construction and application of DRAINMOD model

1) Sensitivity analysis of parameters

The DRAINMOD model requires many input parameters, complicating bioretention system modeling [39,40]. To streamline this process, the modified Morris screening method was employed to assess parameter sensitivity—this method effectively identified the most sensitive parameters for precise calibration (while empirical values were assigned to less influential ones), and the model setup was expedited while reliability was maintained [29]. The sensitivity analysis began by individually perturbing each input parameter while keeping the others fixed, adjusting their values in incremental steps of 10%. The perturbation levels were set to −30%, −20%, −10%, 10%, 20%, and 30% of their original values, and the resulting changes in the output were recorded. Subsequent sensitivity analysis was then performed for the remaining parameters.

Air temperature and rainfall data were input into the model according to the test conditions, with the total runoff control rate serving as the key output parameter for sensitivity analysis. The model showed insensitivity to rainfall intensities between 10 mm/h and 40 mm/h, likely due to the low volume of rainfall-runoff within this range. Under these conditions, the bioretention system could effectively manage the runoff, resulting in unchanged output and, therefore, insensitivity in the parameters. The sensitivity results for a rainfall intensity of 80 mm/h are presented in **Table 3**.

At a rainfall intensity of 80 mm/h, the parameters R, H_1, and k demonstrated a high sensitivity to the total runoff control rate, highlighting their significant impact on model performance. In contrast, variations in R_e, K_R, and K had a minimal effect on the reduction rate of the resultant runoff, indicating that these parameters are relatively insensitive. Therefore, when developing the bioretention system model, it is crucial to ensure the accuracy of R, H_1, and k, as these parameters play a key role in determining the system's reliability. Specifically, R and H_1 serve as the initial design parameters of the bioretention system, with values of 10 cm and 15 cm, respectively, while the empirical value is used for k. The design values for H_2, D_1, and D_2 are each set to 40 cm. Since there is only one drain within the bioretention system, the parameter L is defined as the system's diameter, set to 20 cm. For the parameters deemed insensitive, R_e is set to 25 mm, K_R is determined through the variable-head infiltration test to be 0.0035 cm/h, and k is measured by the constant-head infiltration test to be 50.67 cm/h.

2) Calibration and validation of DRAINMOD model

The calibration of the DRAINMOD model is a necessary condition to ensure the reliability of the model, and by adjusting the key parameters of the model input, the output results of the model are gradually close to the real values, thus improving the degree of agreement between the simulated and measured values and making the model reach the optimization [41]. In this study, the flow production module and infiltration module were calibrated and validated by comparing the simulated values with the actual values under different rainfall conditions and using the coefficient of determination R^2, the relative error RE, and the Nash efficiency coefficient NSE as the evaluation indexes. The main input parameters of the model are as follows: the R was 10, the H_1 was 15 cm, the L was 20 cm, the R_e was 25 cm, the k was 300 cm/d, the H_2 was 40 cm, the K_R was 0.0035 cm/h, the D_1 was 40 cm, the D_2 was 40 cm, the K was 50.67 cm/h.

Fig. 6. (a) shows the comparison between the simulated flow rate and the actual flow rate of the flow production module, and **Fig. 6. (b)** shows the comparison between the simulated infiltration volume and the actual infiltration volume of the infiltration module. The three evaluation indexes of R^2, RE, and NSE after calibration of the flow production model in the confluence area are 0.999, −0.015, and 0.931, respectively; and the three evaluation indexes of R^2, RE, and NSE after rate-setting of the bioretention system model are 0.996, −0.018, and 0.941, respectively. Therefore, the post-rate-setting bioreten-

Table 2. Model input parameter sensitivity analysis table

Parameters	Meaning	Unit	Ranges	SN	Rank
R	Catchment area ratio	\	7-13	−0.672	1
H_1	Height of aquifer	cm	10.5-19.5	0.273	2
L	Spacing between drains	cm	14-26	−0.174	4
R_e	Effective radius of drains	cm	1.75-3.25	0.007	8
K	Drainage coefficient	cm/d	210-390	0.268	3
H_2	Height of internal storage area	cm	28-52	−0.165	5
K_R	K of Restricted Drainage Layer	cm/d	0.0014-0.0026	0.003	9
D_1	Depth of soil layer	cm	28-52	0.121	6
D_2	Depth of filler layer	cm	28-52	0.110	7
K	Permeability coefficient	cm/h	35.469-65.871	0.000	10

[a] $1 \geq |SN| \geq 0.2$ indicating sensitive, $0.2 \geq |SN| \geq 0.05$ indicating medium sensitive, $0.05 \geq |SN| \geq 0$ indicating insensitive.

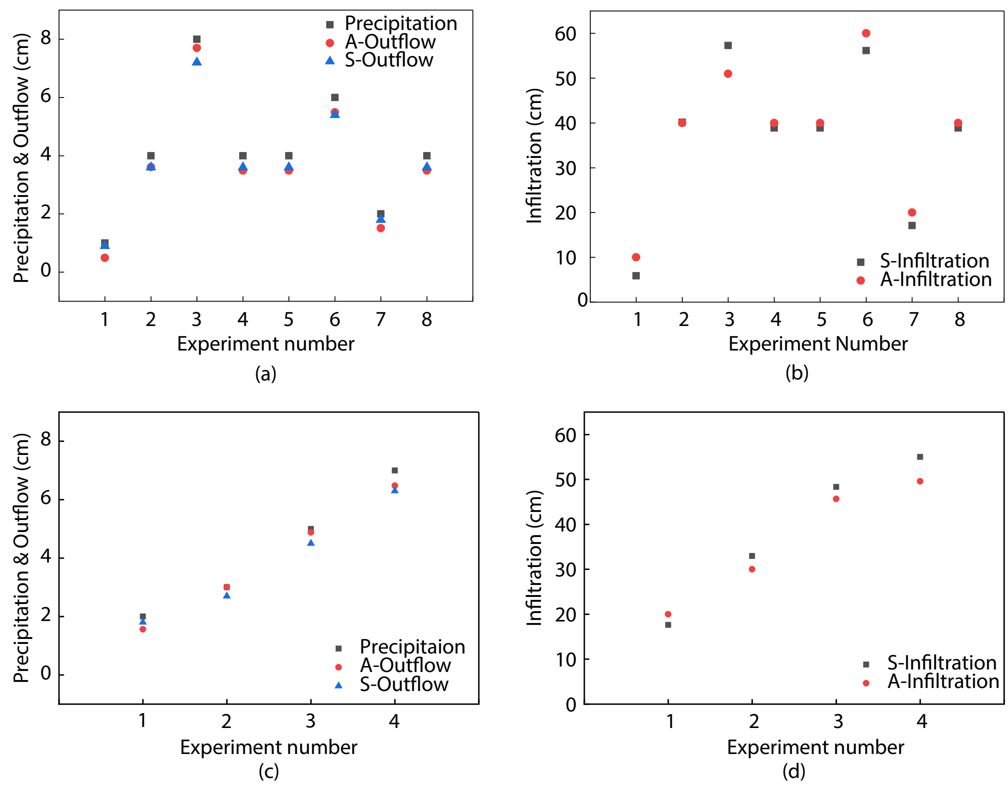

Fig. 6. Calibration and Validation of Bioretention System ((a, b) Calibration: Simulated vs. actual outflow/infiltration; (c, d) Validation: Outflow/infiltration under different rainfall)

tion system model had a good simulation effect for both flow production and infiltration, indicating a high reliability of the model.

Subsequently, the flow production module and the infiltration module within the catchment area were validated under rainfall intensities of 20, 30, 50 and 70 mm/h in turn, and the results are shown in **Fig. 6. (c)(d)**. By comparing the simulated and actual flow production under four groups of different conditions, the R^2, RE and NSE were 1.000, 0.041 and 0.921, respectively; and the comparison of the simulated and actual infiltration volume of the bioretention system showed that the R^2 was 0.993, the RE was 0.060, and the NSE was 0.808. The aforementioned findings show that the models' simulation results are reliable and the models can be used.

3) Analysis of simulation results

After the validation of the DRAINMOD model, the effects of six main parameters including R, H_1, D_1, D_2, H_2, and L on the effectiveness of stormwater runoff control in bioretention sys-

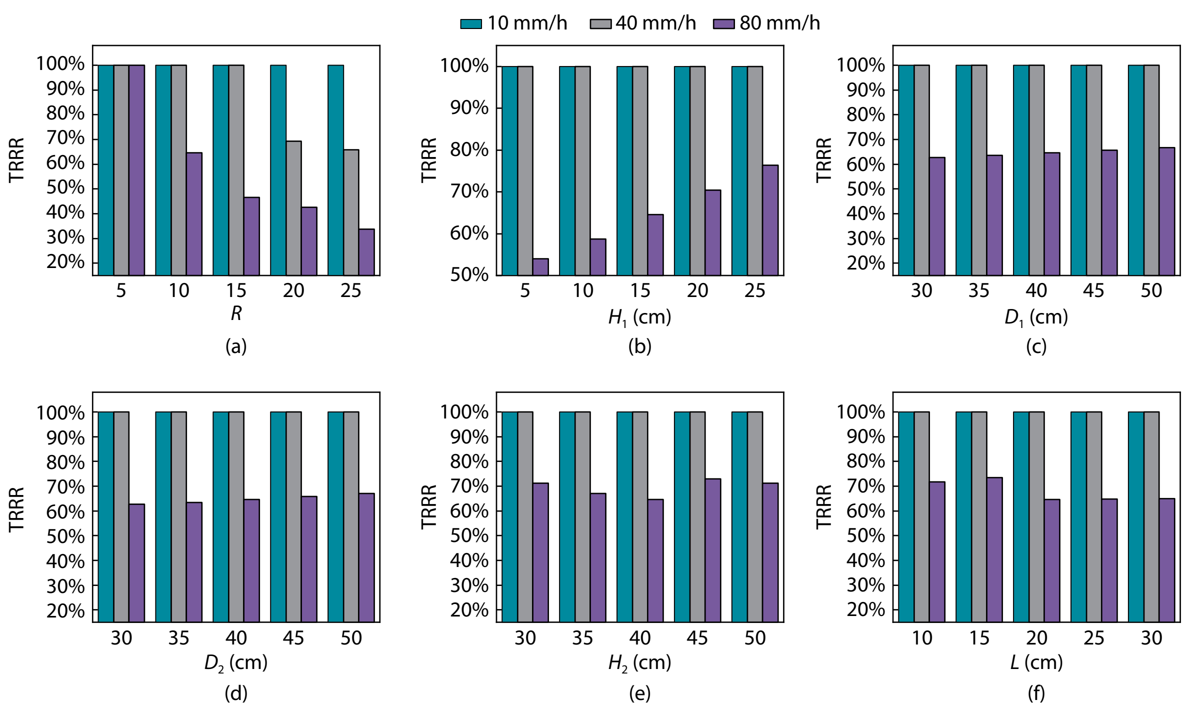

Fig. 7. DRAINMOD simulation of key design parameters' effects on TRRR of bioretention systems (under 10, 40, 80 mm/h rainfall intensities)

tem under different rainfall intensities were generated by the model, and the results are shown in **Fig. 7**.

As shown in **Fig. 7(a)**, the TRRR steadily declined as the catchment area ratio (R) increased. When R increased from 5 to 25, it decreased by 66.3%, resulting in the TRRR of the biological retention system at 80 mm/h dropping from 100% to 33.7%. This decline is mainly due to the strong correlation between the rainwater volume in the catchment area and the catchment area. When the runoff volume exceeds the infiltration capacity of the biological retention system, overflow events also begin to occur and gradually increase, leading to a further decrease in TRRR. Although a smaller R value may lead to underutilization of the stormwater runoff control capacity of bioretention systems, these systems typically offer better runoff control at a lower rate. Therefore, in order to maximize the ability of the biological retention system to control stormwater runoff and improve the overall runoff control rate, it is necessary to further optimize R.

Fig. 7(b) illustrates the impact of the height of the aquifer (H_1) on the TRRR under varying rainfall conditions. When the rainfall intensity was 10 mm/h and 40 mm/h, the TRRR of the bioretention systems remained at 100%, indicating that H1 had the least impact on stormwater runoff under these scenarios. Conversely, when the rainfall intensity is 80 mm/h, H_1 is positively correlated with TRRR. Specifically, as H_1 increased from 5 cm to 25 cm, the corresponding TRRR rose from 54.0% to 76.4%. However, it should be noted that an increase in H_1 can prolong the duration of waterlogging in aquifers, delay the occurrence of root flooding in plants, and under extreme conditions, this may lead to the death of plants due to root rot. Therefore, it is necessary to further optimize H_1 to ensure effective rainwater management while minimizing the duration of excessive flooding for plants.

The effects of the depths of the filler layer (D_1) and soil layer (D_2) on the TRRR are illustrated in **Fig. 7(c)** and **Fig. 7(d)**. It is evident that both D_1 and D_2 have similar influences on TRRR. The bioretention system effectively manages stormwater runoff when rainfall intensity ranges from 10 mm/h to 40 mm/h, indicating that variations in D_1 and D_2 do not affect TRRR within this range. However, at a rainfall intensity of 80 mm/h, the TRRR from the bioretention system is positively correlated with the depths of the media layers. This phenomenon can be attributed to the fact that increasing the depth of the media layers adds more pores to the bioretention system. These additional pores enable the system to retain more rainwater under the same rainfall conditions, thereby increasing the TRRR. Overall, although the increase of D_1 and D_2 may improve performance in some aspects, their impact on TRRR is relatively unfavorable.

Regarding H_2 (**Fig. 7(e)**), the TRRR of the bioretention system was 100% at rainfall intensities of 10 mm/h and 40 mm/h. However, at a rainfall intensity of 80 mm/h, the TRRR exhibited a tendency to first decrease, then increase, and subsequently decrease again as H_2 increased. The TRRR remained within a range of 64.6% to 72.9%. This pattern might be attributed to the increase in the height of the aquifer within the water storage area, which reduces the distance between the outlet of the biological interception system and the surface. As a result, due to the reduction in the potential energy difference between the rainwater stored in the aquifer and its outlet, the outflow rate decreases.

The capacity of a bioretention system's drainage layer can be adjusted by varying the distance L, which affects the TRRR of the system. As shown in **Fig. 7(f)**, the total TRRR is 100% for rainfall intensities of 10 mm/h and 40 mm/h, indicating that the effects of L on TRRR are not significant under these conditions. However, at a rainfall intensity of 80 mm/h, the TRRR exhibited a trend of initially increasing, then decreasing, and ultimately stabilizing as L increased. This phenomenon may be attributed to the fact that increasing L from 10 cm to 15 cm can enable each drainage outlet to cover a larger drainage area, thereby enhancing the drainage capacity of the biofilm retention system and reducing TRRR. On the contrary, when the distance between the drainage pipes is further increased to 20 centimeters, there is an area between the two drainage pipes that cannot effectively drain water, resulting in a decline in the overall drainage capacity of the biological interception system. To enhance the drainage capacity of the drainage holes in the biological retention system, it is necessary to further optimize the distance between the drainage holes.

In conclusion, parameters D_1, D_2, and H_2 have a relatively minor impact on the bioretention system's runoff management capabilities. Effective runoff control and pollutant removal necessitate that the depth of the media layer in the bioretention system maintains sufficient water availability to support healthy plant growth. Additionally, the internal storage area must be designed to prevent excessive waterlogging of the plant root system, which justifies the selection of a 30 cm soil layer, a 40 cm filler layer, and a 40 cm internal storage height. Based on the above results, parameters R, H_1, and L require further optimization due to their varying influences on the TRRR of the bioretention system.

3.2.2. Parameter optimization via response surface methodology

Response Surface Analysis was used in this study to optimally design the three parameters of the bioretention system's R, H_1, and L under the conditions of 80 mm/h rainfall intensity, 1 h rainfall duration, and 1 d ADD. This study adopts the simulation results of the DRAINMOD model. The experimental scheme and simulation results are shown in **Table S6**. Subsequently, a second-order model was adopted to fit the experimental results, and analysis of variance and significance tests were conducted on the model (**Table S7**).

The P-value of the fitting model is less than 0.05, indicating that the model is significant and has a high fitting accuracy. This model can be used to optimize the design of bioretention systems [42]. Furthermore, the P-values for the three parameters —R, H_1, and L —are all less than 0.05, which similarly demonstrates that R, H_1, and L significantly influence the effectiveness of stormwater runoff control, confirming the appropriateness of the parameter selection.

Based on the simulation results of DRAINMOD, the multivariate quadratic regression equations between TRRR (%) and various factors established by the response surface methodology are as follows：

$$Y = -0.1332 * A + 0.0528 * B - 0.0326 * C - 0.0102 * AB + 0.0116 * AC - 0.0268 * BC + 0.0377 * A^2 + 0.0134 * B^2 + 0.0423 * C^2 + 0.466 \quad (8)$$

Where A is R; B is H_1, cm; C is L, cm.

The response surface fitted regression equation was further analyzed statistically for errors, with the results presented in **Table S8**. The fitted regression equation has a very good correlation, with an R^2 value of 0.9945. This equation effectively explains the impact of changes in the design parameters of the bioretention system on TRRR, especially when the difference between the adjusted R^2 and the predicted R^2 is less than 0.2, indicating that no additional design parameters are required. The sufficiency accuracy value of 40.3925 exceeds 4, further supporting the rationality of the fitting regression equation. The coefficient of variation (CV) is 2.47%, which is lower than the 10% threshold, indicating that the fitted regression equation has good accuracy and reliability.

The normal probability plot demonstrates the distribution of externally studentized residuals against the expected normal distribution **Fig. 8** **(a)**. The data points are closely aligned with the reference line, indicating that the residuals are approximately normally distributed. This is a key assumption in regression analysis because it indicates that the model's error does not exhibit systematic bias and is randomly distributed. Minor deviations observed in extreme cases may require further investigation, but overall, the model seems to satisfy the normality assumption. The scatter plot of externally studentized residuals against predicted values reveals important information regarding the model's fit **Fig. 8** **(b)**. The horizontal red line represents the critical threshold for identifying potential outliers, which is set to ±4.82. Most residuals fall within this range, indicating that the majority of observations will not have an undue impact on the model. However, several points exceeded these thresholds, indicating that they might be influential outliers. The distribution of the residuals near the zero line further supports the sufficiency of the model, as there is no obvious pattern indicating that the variance of the residuals is constant. The plot comparing actual versus predicted values illustrates the model's predictive accuracy **Fig. 8** **(c)**. The data points are closely distributed around the 45-degree reference line, indicating a perfect prediction. The high correlation between the actual values and the predicted values indicates that the model effectively captures the potential relationships in the data. The proximity of the point to the straight line indicates strong predictive ability and enhances the effectiveness of the model.

Additionally, response surface analysis allows fixing one of the three factors at its central value to explore the interaction between the other two. It also provides a three-dimensional response surface plot of the total runoff reduction rate under these interactions, as shown in **Fig. 8** **(d-f)**. In **Fig. 8** **(d),** the three-dimensional plot shows no maximum point for the total runoff reduction rate; however, a maximum of 70.5% occurs when the drainage area ratio (R) is 10 and the storage layer height (H_1) is 20 cm. The total runoff reduction rate decreases rapidly with increasing R and increases slowly with H_1, indicating that R has a more significant impact on stormwater runoff control. The land area of Coral Island is limited and it relies on scattered small facilities, as described in Section 1. The optimized R value is within the adaptive R range of 7 to 13 for coral islands and matches the typical water collection ratio of the coral island plots. This balance avoids excessive land occupation and insufficient runoff control. **Fig. 8** **(e)** reveals a maximum total runoff reduction rate when the spacing of the perforated drainage pipes (L) is 10 cm and R is 10. As L increases, the total runoff reduction rate decreases rapidly at first and then stabilizes, showing that R has a more pronounced effect. In **Fig. 8** **(f)** with H_1 at 20 cm and L at 10 cm, the total runoff reduction rate reaches 70.5%. As H_1 increases, the total runoff reduction rate rises quickly, indicating H_1's greater influence compared to L.

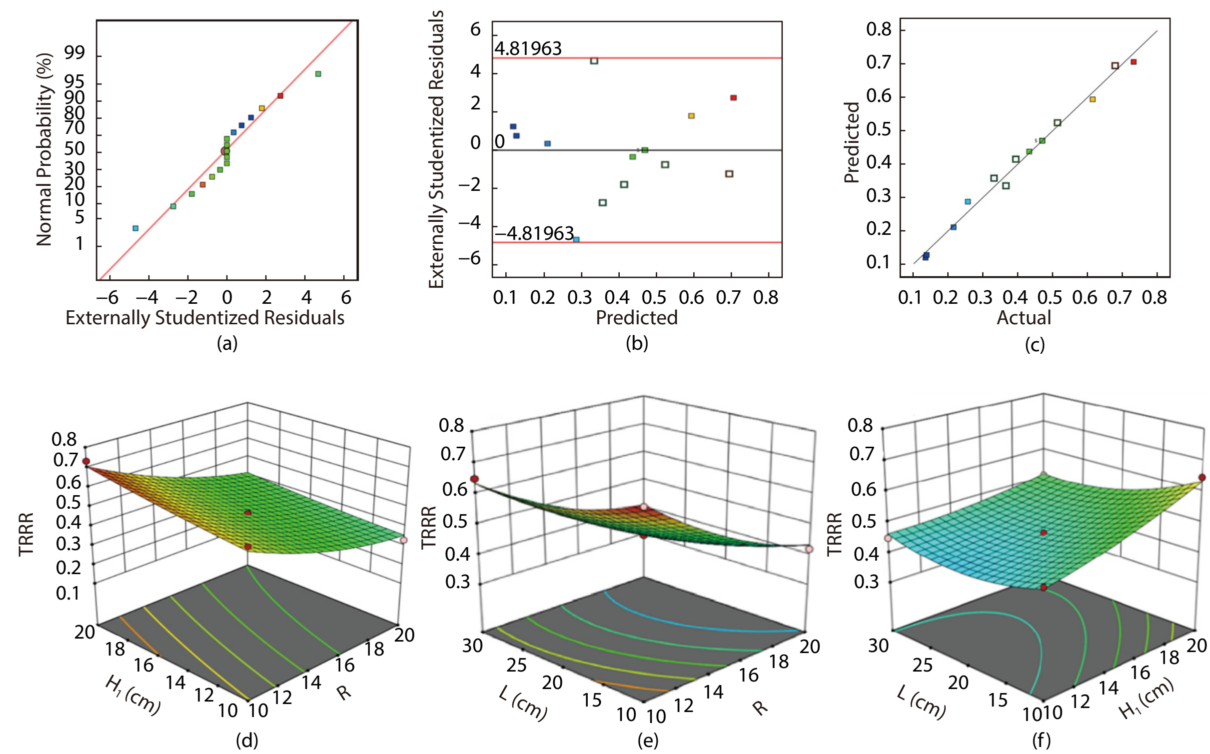

Fig. 8. Analysis of Response Surface Model Performance and Influencing Factors

In summary, while R, H_1, and L all significantly affect the total runoff reduction rate, R is the most significant, followed by H_1, and then L. The interaction between $H_1$and L is significant, while the interactions involving R are not.

After the calibration of the fitting equations, the optimal design parameters of the bioretention system were obtained with the objective of the highest TRRR reduction, where the R was 10.113, the H_1 was 19.62 cm, the L was 17.85 cm, and the simulated TRRR reduction was 71.8 % (**Fig. 9**).

3.3. Actual operation of optimized bioretention system

Based on the design parameter optimization results from the response surface analysis, we constructed the bioretention system with D_1 of 30 cm, D_2 of 40 cm, H_1 of 40 cm, R of 10.113, H_2 of 19.6 cm, and L of 17.9 cm. Investigations were conducted on the hydrological characteristic curve, changes in water content under actual rainfall scenarios, and the elimination of TSS.

3.3.1. Comparison of hydrological characteristic curves after optimization

Fig. 10 illustrates the comparison of hydrological characteristic curves before and after the optimization of the design parameters. It is obvious that under all rainfall conditions, except for a rainfall intensity of 80 mm/h, no overflow occurred in the biological retention system. At this intensity, the TRRR of the optimized bioretention system reached 67.7%, closely aligning with the predicted model value of 71.8% and surpassing the pre-optimization runoff reduction rate of 60.0%. The runoff delay time improved to 28 minutes, compared to the pre-optimization delay time of 19 minutes. The optimized bioretention system also demonstrated enhanced flood peak control, with peak flow reduction increasing from 42.9% to 46.4% and a delay in flood peak arrival time to 28 minutes, indicating superior hydrologic performance. Overall, under identical rainfall

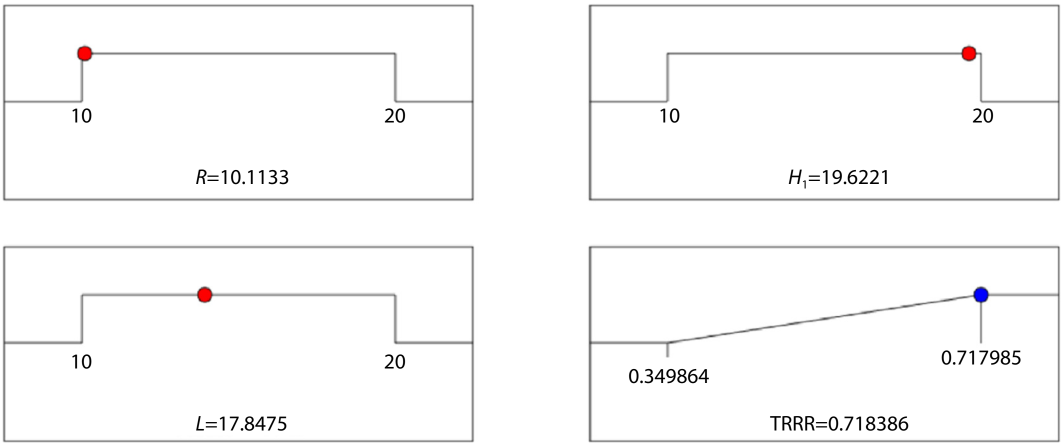

Fig. 9. Optimum test conditions for response surface testing

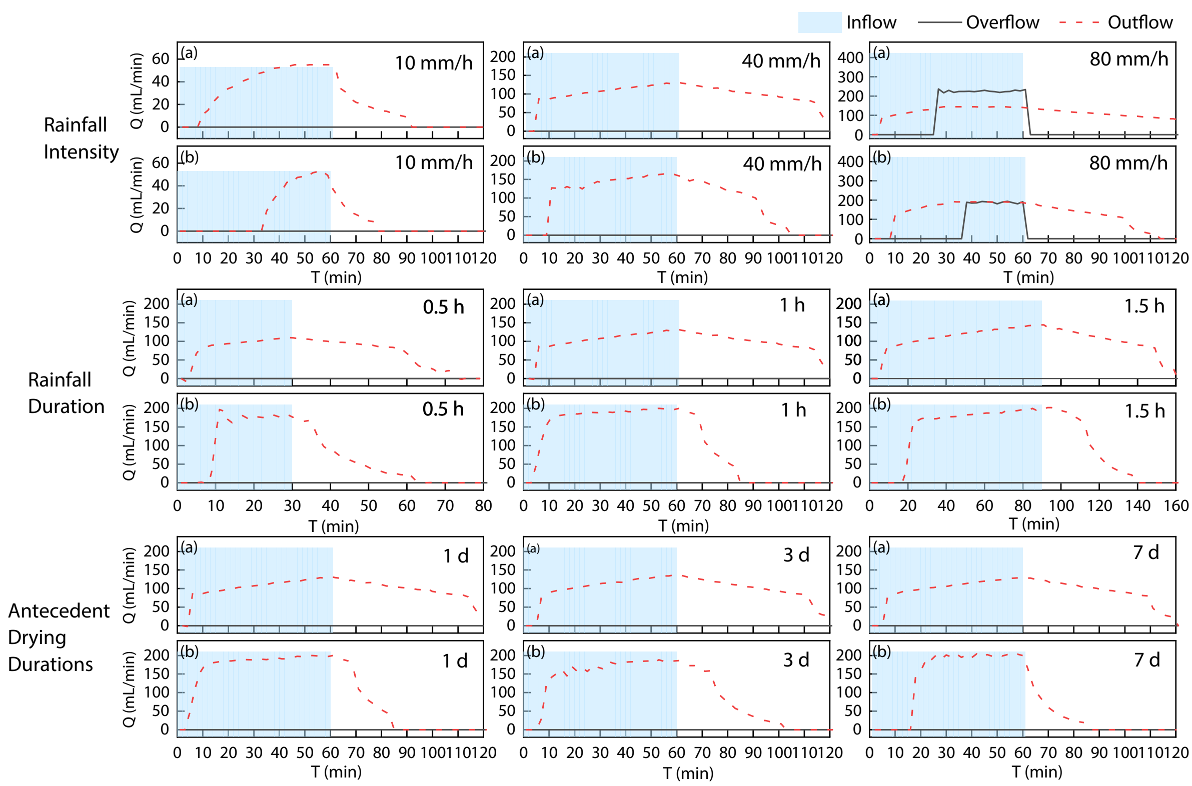

Fig. 10. Comparison of hydrological characteristic curves after optimization(a refers to the column numbered B1; b refers to the optimized bioretention system)

conditions, the optimized bioretention system consistently extended the duration of water retention before reaching the outlet. This improvement might be due to the fill height being reduced from 80 cm to 70 cm, thereby lowering the potential energy of stormwater runoff and thus reducing the water output. However, the optimized system exhibited a slightly higher flow rate than before optimization, likely due to the decrease in the soil layer height from 40 cm to 30 cm, which reduced pore space and subsequently the water-holding capacity of the system.

3.3.2. Changes in water content in bioretention systems under actual rainfall scenarios

In order to enhance the evaluation of the water content changes in the optimized biological retention system, a long-term field test simulating actual rainfall conditions was conducted on the coral island. The results comparing the water content at 10 cm and 30 cm depths in the soil layer between the optimized bioretention system (A) and the pure coral sand bioretention system (B) are as follows:

1） Water content changes during the rainy season

Fig.11 **(a)** illustrates the variations in soil layer water content of the bioretention system over time and in response to rainfall during the rainy season. It is evident that the water content varies significantly with soil depth, with deeper layers consistently displaying higher water content levels. This observation indicates that soil depth is a key factor influencing the water retention capacity of biological water retention systems.

Moreover, bioretention system A exhibited consistently higher water content compared to system B, regardless of rainfall intensity. During the 30-day rainy season simulation, the average water content in system A was 21.6% at a depth of 10 cm and 37.5% at a depth of 30 cm, while system B recorded averages of 14.0% and 16.9% at these respective depths. Thus, system A demonstrated water content levels that were 7.6% and 20.6% higher than those in system B. These results indicate that the soil layer of System A has good water retention, which supports the healthy growth of plants in the bioretention systems and is more suitable for use on coral islands.

2） Water content changes during the dry season

Fig.11 **(b)** illustrates the changes in soil layer water content of the bioretention systems over time in response to rainfall during the dry season. Two main observations emerged from the 30-day experiments. First, system A was able to maintain a high water content in the soil layers at depths of 10 cm and 30 cm even after a 10-day drying period. Specifically, during the D1–D10 test, system A sustained water content levels of 17.2% at 10 cm and 31.2% at 30 cm, whereas system B exhibited significantly lower water content levels of 11.3% and 11.7% at the same depths. Second, while both systems A and B reached saturated water content following heavy rainfall, system A showed a much slower decline in water content compared to system B. After the heavy rainfall at D10, the initial water content levels of systems A and B at depths of 10 cm and 30 cm were 20.7%, 36.0%, 14.5%, and 16.7%, respectively. Following a 12-day drying period, these values decreased to 19.4%, 33.5%, 12.1%, and 13.1%. These results clearly indicate that the water retention capacity of system A is significantly stronger than that of System b. This significant improvement in water retention capacity provides more stable water support for the growth of typical coral island vegetation, effectively reducing the adverse effects of soil drought on vegetation growth.

3.3.3. TSS removal efficiency of the optimized bioretention system

Fig.12 shows the effectiveness of the optimized bioretention system in removing TSS under simulated rainy and dry season rainfall conditions in the coral island region. During each simulated rainfall event, the influent TSS concentration was set to 250 mg/L using red soil as the representative pollutant. The experimental results indicate that the bioretention system consistently demonstrates excellent TSS removal efficiency, regardless of whether it is the rainy or dry season. Throughout the trials, the effluent TSS concentration remained below 4 mg/L following precipitation, with an overall TSS removal rate consistently exceeding 98.7%. These findings suggest that the medium within the bioretention system exhibits strong physical filtration and chemical adsorption capabilities.

4. Conclusions

In this study, three methods of Analytic Hierarchical Process, DRAINMOD, and Response Surface Methodology were combined to conduct a multi-dimensional comparative analysis of bioretention system for coral islands from filler selection to parameter optimization. Ultimately, we developed a bioreten-

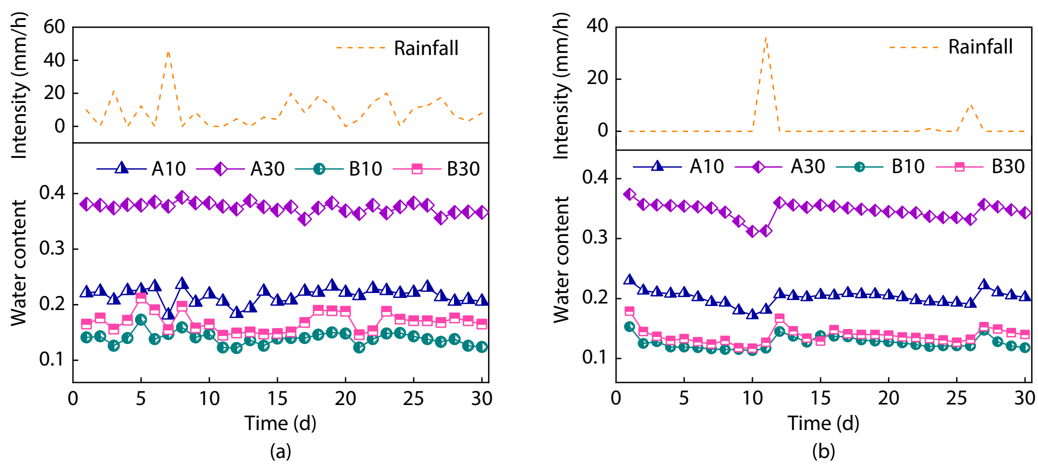

Fig. 11. Water content and rainfall intensity of soil during the rainy/dry season (A represents the optimized bioretention system, while B refers to the column numbered B1)

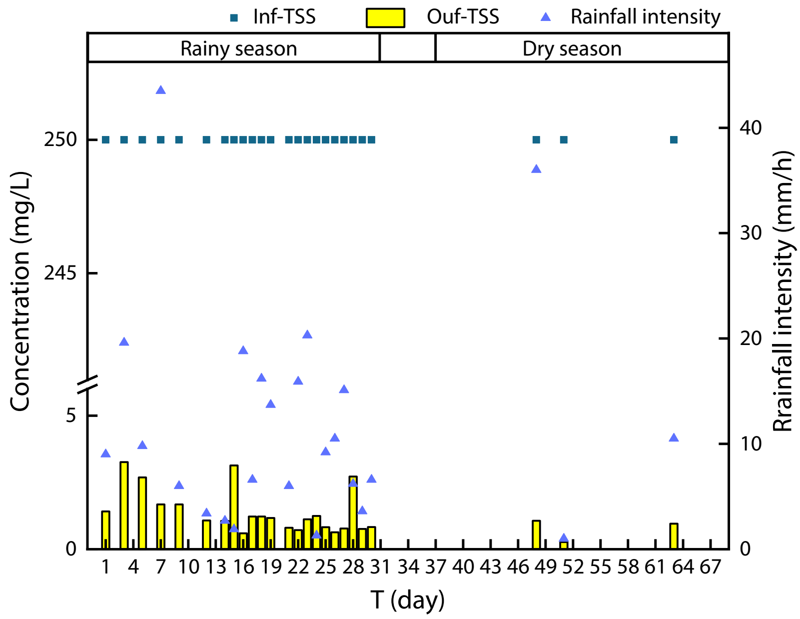

Fig. 12. TSS removal efficiency of the optimized bioretention system

tion system for coral islands that demonstrated improved hydrological performance, enhanced water retention, and effective TSS removal. The specific results are as follows:

1) Considering the cost of fillers, stormwater runoff control effectiveness, TSS control efficiency, and the rate of water content reduction in the soil layer, a hierarchical analysis was carried out to determine a suitable combination of filler for bioretention system on coral island: coral sand mixed with red soil (9:1) was used as the soil layer, and coral sand mixed with vermiculite (9:1) was used as the filler layer.

2) The established DRAINMOD model accurately predicts the hydrological effects of coral sand bioretention systems. The evaluation indices R^2, RE, and NSE after the flow production model's rate-setting in the confluence area are 0.999, −0.015, and 0.931, respectively. After calibrating the bioretention system model, these indices are 0.996, −0.018, and 0.941, indicating high reliability of the model.

3) The design parameters of the bioretention system were further optimized through response surface analysis. Simulation results indicated that with a catchment area ratio (R) of 10.307, aquifer height (H_1) of 19.38 cm, and spacing between drains (L) of 17.85 cm, the bioretention system achieved maximum runoff control efficiency, with a TRRR of 71.8%.

4) The performance of the parameter-optimized bioretention system during long-term operation simulating actual rainy and dry season rainfall on a coral island is as follows: For runoff control, under heavy rainfall conditions, the total TRRR of the system was 67.7%, an increase from the pre-optimization total runoff reduction of 60.0%. For water content retention, the average water content of the modified coral sand bioretention system at depths of 10 cm and 30 cm during the rainy season was 7.6% and 20.6% higher than that of the pure coral sand bioretention system, respectively. For TSS removal, the overall TSS removal rate consistently exceeded 98.7%, with effluent TSS concentrations maintained below 4 mg/L.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Electronic Supplementary Material (ESM)

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