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Research on Ecological Lawn Regulation and Storage System in Flight Area Based on Sponge Airport

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Abstract: Through the construction of an ecological lawn regulation and storage system, the adaptability of airports to extreme weather can be enhanced. The problems of runoff, ponding and pollution faced by traditional airport flight areas during heavy rainfall can be solved, and the utilization efficiency of rainwater resources can be improved. In this paper, the SWMM is used to simulate and analyze an 4E-level airport of a certain city in Region III as the research object. The simulation results show that the ecological lawn regulation and storage system can significantly reduce runoff flow, ponding durations and runoff pollution with different return periods. In addition, the water storage module of the system can store 24,000 m^3 of water and recycle it. This research proves that the ecological lawn regulation and storage system can effectively improve the rainwater control capability of the airport flight area, which has an important reference value for the sponge transformation of traditional airports and is helpful to promote green civil aviation construction and sustainable development.

Keywords: sponge airport; flight area; ecological lawn regulation; storage system; SWMM simulation

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1. Introduction

The Civil Aviation Administration of China has formulated the "Outline for Development of Green Aviation Manufacturing Industry" (2023–2035) [1], which proposes the goals of green civil aviation construction, such as energy conservation, pollution reduction, carbon reduction and green expansion. A sponge airport [2,3] is an airport stormwater management concept of a new generation under the background of the sponge city. The core of its construction is to absorb, store and purify water during rainfall and release the stored rainwater if necessary to improve the utilization rate of the airport's rainwater resources. A sponge airport is able to enhance the airport's ability to cope with extreme weather and achieve the comprehensive goals of green airport construction such as energy conservation, pollution reduction and rainwater resource utilization [4]. Newly built airports such as Beijing Daxing International Airport and Qingdao Jiaodong International Airport have applied the concept of the sponge airport to build new-type airports with holistic green rainwater management systems. The sewage treatment rate and the recycled water utilization rate of Beijing Daxing International Airport have reached 100% [5], while Qingdao Jiaodong International Airport has achieved the targets of a rainwater runoff control rate of 75% and a recycled water utilization rate of over 50% [6], which have played a leading demonstrative role and verified the feasibility and necessity of sponge airport construction.

There are over 200 civil transport airports in China, which are classified into the five levels of 3C, 4C, 4D, 4E and 4F [7], from small to large. The 4E-level airports account for the largest proportion of the total number of the airports and have a large number of flights. Most of them are traditional airports without the rainwater management system of the sponge airport. Traditional airports adopt the treatment methods of "rapid drainage of rainwater" and "terminal centralization", which mainly rely on drainage pipelines and pump stations, with single flood control and drainage measures [8]. Therefore, on the one hand, heavy rainfall places enormous pressure on the airport's drainage network. The rapid speed of surface rainwater runoff causes the problem of waterlogging in the flight area, and even the efficiency of the airport's operational safety could be affected by prolonged ponding durations in severe cases. On the other hand, the surfaces of runways in the airport flight area are contaminated with oil, rubber and chemical products such as de-icing waste liquid and de-oiling waste water, resulting in a high concentration of initial rainwater runoff pollution. If such rainwater is discharged directly into the municipal rainwater sewer system or the airport enclosure river without treatment, the problem of downstream water pollution will occur.

The SWMM (stormwater management model) [9] is a dynamic precipitation runoff simulation model mainly used to simulate a single precipitation event or long-term water quantity and quality simulation in cities. This paper addresses the issues of runoff, water accumulation and pollution faced by traditional airport airfield drainage systems during heavy rainfall by proposing an improvement plan based on the sponge city concept. The core research question is how to effectively enhance the drainage capacity and water quality control of traditional airport airfields in response to increasingly frequent extreme rainfall events. To this end, the study selects a 4E-level airport in a city within Region III as the research object and puts forward the following scientific hypothesis: by introducing an ecological lawn storage system combined with gray infrastructure, the hydrological control and water quality of the airport airfield can be significantly improved. The study first conceptualizes the airport airfield drainage system and then constructs the ecological lawn storage system. Subsequently, the SWMM is used to simulate the proposed improvement plan, analyzing its effects on water quantity regulation and water quality improvement. The goal of the research is to provide effective theoretical and practical references for the sponge city transformation of traditional airport airfields, thereby enhancing airports' flood control and drainage capacity in the face of heavy rainfall, which holds significant practical importance.

2. Modeling of Rainwater System in Research Area

2.1. Present Situation of Research Area

A certain 4E-level airport is selected for analysis. This area is located in the north of China at an altitude of 3 m. It has a warm temperate semi-humid continental monsoon climate. The spring here is dry with little rain, while the summer is hot with a concentrated rainy season. The annual precipitation is 500–700 mm [10], mainly concentrated in the summer. A large amount of instantaneous rainfall causes a sudden rise in the water level of the river, easily resulting in poor drainage and consequent waterlogging. According to statistics, the airport has experienced over 20 rainfall events leading to waterlogging since 2008, which have posed serious potential risks for the efficient operation of the airport.

The overall flight area of the airport is high in the west and low in the east, with a relatively flat terrain. The area of hardened runways in the flight area is about 240×10^4 m^2 [11], and the area of the soil and green space is about 4600×10^4 m^2 [11]. The groundwater level in the area is high, and the infiltration capacity of the soil is limited. The corresponding geographic and hydrologic characteristics make the area prone to short-duration and high-intensity rainstorms in summer, resulting in rapid rainwater collection in the area at that time, which puts high pressure on the drainage pipes in a short time. Most of the turfgrass ditches suffer from varying degrees of siltation, leading to rainwater collection on the surface and consequent waterlogging. The siltation has also caused the problem of the overgrowth of weeds in the drainage ditches in the flight area. The grassland vegetation consists mostly of perennial or annual common weeds, with the main dominant species [11] including *Lagopsis supina*, *Roegneria ciliaris*, *Hemistepta lyrata*, *Ixeridium chinense*, *Chenopodium glaucum*, etc. The birds attracted by the weeds with serious impacts are red falcons (*Falco tinnunculus*), magpies (*Pica pica*) and sparrows (*Passer montanus*), which have impacts on bird-strike prevention at the airport (Figure 1).

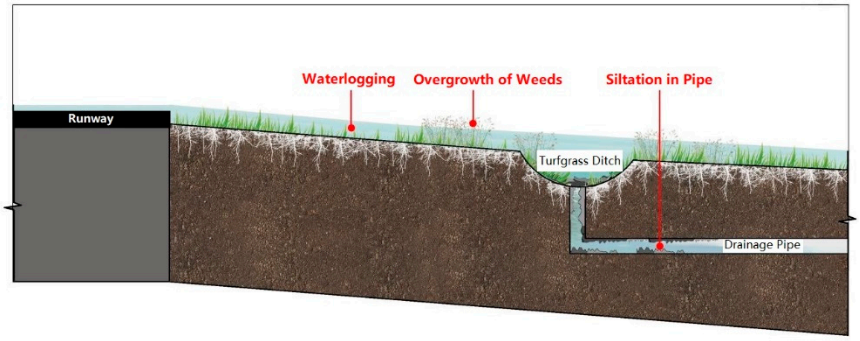

Figure 1. Present situation and problems in the airport flight area.

2.2. Generalization of Rainwater System

The SWMM is used to generalize the rainwater system in the airport flight area based on the rainwater pipe network data provided by the airport and fieldwork on the rainwater pipe network. The airport flight area is divided into two runways, east and west, and currently mainly operates on the west runway. This paper mainly focuses on the simulation and analysis of the west runway. The study area has a relatively small catchment area, and the changes in land type before and after construction are straightforward. Additionally, comprehensive data on the region's drainage network and topography are available, which allows for the use of manual delineation methods to divide the sub-catchments. Using the airport flight area construction blueprints, the area and width of each sub-catchment were determined. Elevation data, satellite maps and land use type information were utilized to establish the Manning's coefficient, depression storage, impervious area ratio and slope of each sub-catchment. Furthermore, the rainwater drainage network diagrams and corresponding data provided necessary parameters such as the length, dimensions, starting and ending depths and slopes of the drainage pipes. After manually delineating [12] the sub-catchments accurately, the processed data were imported into the SWMM (stormwater management model) for modeling. This approach ensures that the model reflects the physical characteristics and hydrological dynamics of the airport flight area accurately, allowing for the precise simulation of stormwater runoff and management. In the model, the ponding collection points in the catchment area are generalized as nodes, and the drainage open ditches and covered blind ditches are generalized as pipelines. The drainage outlets, pump stations and reservoirs are consistent with their actual locations in the airport flight area. A total of 161 sub-catchment areas, 74 nodes, eight drainage outlets, 81 sections of sewers and two reservoirs are generalized (Figure 2).

This paper adopts the method of calibrating the model parameters using the runoff coefficient [13,14] and verifying the calibration parameters based on the measured rainfall and waterlogging statistics of a certain scene [15]. Referring to the relevant literature, the following value ranges of the parameters are set: the roughness coefficient of the impermeable area is 0.011–0.024 [16], the roughness coefficient of the permeable area is 0.060–0.240 [17] and the roughness coefficient of the pipe is 0.009–0.0150 [18]; the storage capacity of the impermeable area and depression are 1.50–3.50 mm and 2.54–7.62 mm, respectively [14]; and the maximum and minimum infiltration rates are 72.00–78.00 mm/h and 3.18–3.82 mm/h, respectively [19], with an attenuation constant within 2–7 /h. By calibrating the parameters, two rainfall processes with return periods of 3 years and 5 years are simulated, with the simulated runoff coefficients of 0.66 and 0.70, respectively. According to the GB 50014-2021 [20], the numerical simulation values meet the comprehensive runoff coefficients of the research area within the range of 0.6–0.7. The SWMM of the research area is stable and has the required accuracy.

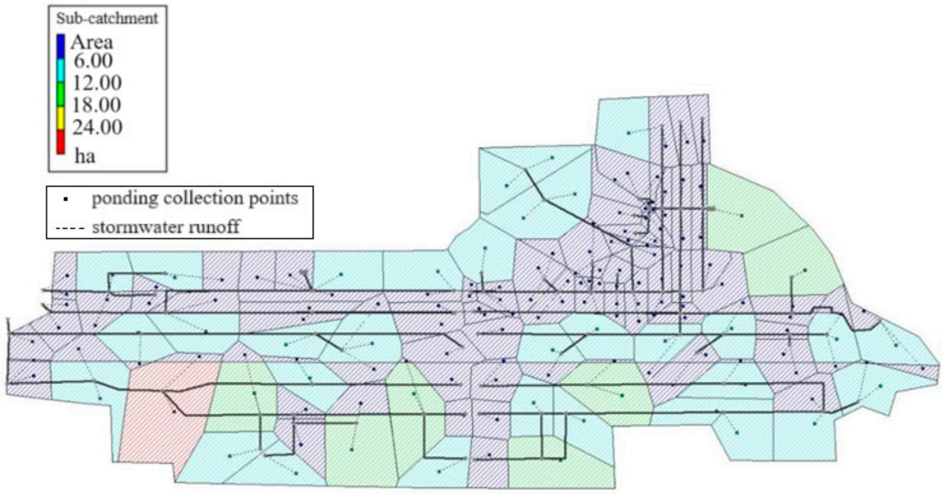

Figure 2. Generalization of the rainwater system in the airport flight area.

2.3. Rainwater Data

Most of the precipitation in China is unimodal, which is similar to the Chicago rainfall pattern. The Chicago rainfall pattern is currently the most widely used rainfall pattern in China. This synthetic rainfall hydrograph proposed by Keifer et al. [21] in 1957 is able to summarize most rainfall patterns and reflect the average characteristics of rainfall processes. Therefore, the Chicago rainfall pattern is taken as the design rainfall pattern, and based on the mathematical statistics method of the drainage management office in the research area, the calculation formula of the rainstorm intensity in the area is as follows:

$$q = \frac{3833.34(1 + 0.85lgP)}{(t + 17)^{0.85}} \quad (1)$$

where q is the design rainstorm intensity, L/(s·hm^2); P is the design return period, a; and t is the precipitation duration, min.

According to the GB50014-2021 [20], airports belong to transportation hubs and their rainwater sewers are designed with a return period of 5–10 years. The construction of the airport's rainwater sewers in the research area is in a relatively early phase, with a relatively low standard for the flood control and drainage system and the pipe network, and the construction standard for rainwater sewers in the flight area is a 5-year return period, which has brought hidden dangers to the operational safety of the airport in the current climate of frequent rainstorms. Therefore, precipitation scenarios are designed with different return periods of 5a, 10a, 20a, 30a, 50a and 100a to compare and analyze the flood control and drainage and the water quality improvement under different heavy rainfall scenarios.

After determining the precipitation intensity, it is also necessary to determine the precipitation pattern, which is represented by the peak coefficient r (the ratio of the peak duration to the rainstorm duration) [22]. The rainstorm hydrographs with different return periods are fitted with a peak coefficient r = 0.375 and a precipitation duration of 120 min (Figure 3) [23]. The rainwater data are imported into the SWMM to obtain a model with precipitation return periods of 5a, 10a, 20a, 30a, 50a and 100a in the research area.

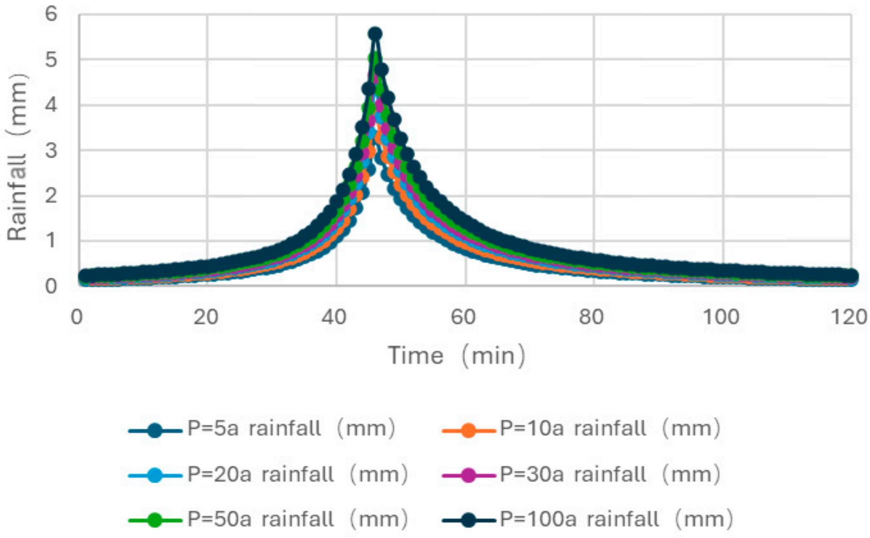

Figure 3. Rainstorm hydrographs with different return periods.

3. Design of Ecological Lawn Regulation and Storage System in Flight Area

Low-Impact Development of Flight Area

Low-impact development (LID) [24,25] is a concept that emphasizes small-scale and decentralized source control based on the concept system of the sponge city in order to achieve the goals of the total flow of rainwater runoff, the peak value of runoff, runoff pollution, waterlogging control, etc. LID facilities mainly include sunken green spaces, grass-planted ditches, rainwater gardens, green roofs, underground storage and infiltration, permeable pavements, etc.

The sponge airport is different from other spaces in the sponge city in that hardened pavements account for a huge proportion and are prone to flood disasters in rainstorms. There is also a problem of high levels of COD (chemical oxygen demand), TN (total nitrogen), TP (total phosphorus), TSS (total suspended solids) [26] and other pollutants in rainwater runoff due to pollutants such as de-icing waste liquid, oil and chemicals in the flight area. During the construction of LID facilities, it is necessary not only to solve the problem of airport flood control and drainage but also to pay attention to the problem of initial rainwater pollution. In addition, airports have special requirements for operational safety, clearance and other aspects. During the construction of LID facilities in the sponge airport flight area, the presence of anything that affects airport clearance, such as tall vegetation and trees, is not allowed, and planting also needs to meet the requirements of bird-strike prevention [27,28].

The characteristics of traditional airport flight areas are mainly covered by runways and green spaces, with a large area of lawn surrounding the runways and taxiways. Therefore, the low-impact development measures for the sponge airport flight area are suitable for choosing grass-planted ditches and sunken green spaces for the "infiltration, retention, storage, purification, utilization, drainage" of rainwater [29].

During light rainfall, a lawn with fine roots is able to increase the resistance of surface runoff and reduce the surface runoff. A retention channel is able to physically separate the surfaces of runways from the large area of lawn to quickly discharge the surface runoff from the surface of runways [30,31]. A filter screen is equipped at the top of the retention channel [32] to reduce the initial rainwater runoff pollution. The inner side of the retention channel consists of permeable bricks and a water level sensor, which are used to capture the change in water level in the retention channel then feed back to the intelligent terminal and slowly release the retained rainwater to the surrounding area through the permeation effect of permeable bricks for a long time after the rainfall. During moderate rainfall, the water level sensor in the retention channel transmits the rising rate of the water level to the intelligent terminal in real time. If the rising rate of the water level is too fast, the intelligent terminal will open the intelligent valve to discharge rainwater into the water storage module [33] through an overflow pipe. The water storage module also stores surface runoff, which is set below a sunken ground area and covered with coarse sand and large stones to reduce the phenomena of siltation and the overgrowth of weeds in traditional turfgrass ditches. The rainwater in the water storage module is purified and recycled to irrigate the lawn after the rainfall. During heavy rainfall, the water level sensor and the intelligent terminal indicate when the retention channel and the water storage module are unable to carry the total amount of rainfall. After the retention channel and the water storage module are full, the intelligent valve is opened to quickly discharge the overflow rainwater through the drainage pipes (Figure 4).

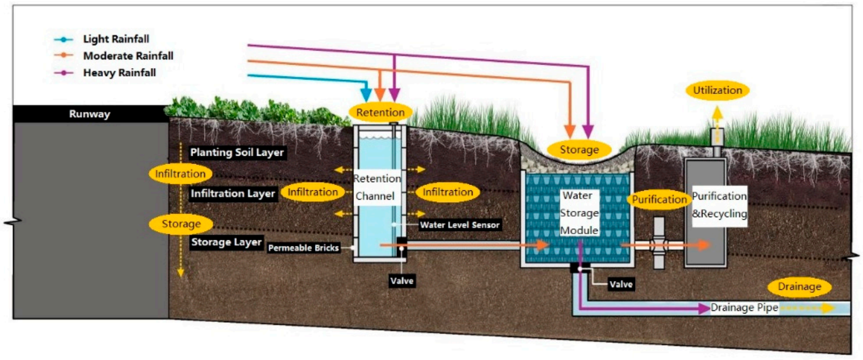

Figure 4. Ecological lawn regulation and storage system.

In order to reduce the bird-strike safety issues, the ecological lawn regulation and storage system needs to remove weeds from the airport flight area and then select and plant vegetation commonly used in sponge airports based on the ecological environment of the airport. According to the birds attracted by the research area with serious impacts, vegetation with fine roots that is not a food source for birds such as red falcons (*Falco tinnunculus*), magpies (*Pica pica*) and sparrows (*Passer montanus*) [34,35] is selected: Dichondra micrantha Urban, *Pennisetum clandestinum* Hochst and *Poa annua* L. [36]. The ecological lawn is planted from top to bottom in order of green vegetation layer, planting soil layer, infiltration layer and storage layer. Through different proportions of the mixed configuration, the cost of the lawn planting is reduced while ensuring the optimal soil hydraulic properties (Table 1).

Table 1. Method for ecological lawn planting.

	Thickness	Mixed Configuration	
Planting soil layer	300 mm	*Dichondra micrantha* Urban	10 g/m^2 Seed quantity, 75% fine sand, 20% Yellow soil, 5% peat mold
		Pennisetum clandestinum Hochst	15 g/m^2 Seed quantity, 85% very fine sand, 10% Yellow soil, 5% peat mold
		Poa annua L.	20 g/m^2 Seed quantity, 50% fine sand, 45% Yellow soil, 5% peat mold
Infiltration layer	400 mm	20% Peat mold, 75% roseite, 5% charcoal	
Storage layer	200 mm	25% Sandy loam, 25% pearlite, 50% bran mix	

4. Simulation Analysis of Design Results

The SWMM is used to simulate the design results of the ecological lawn regulation and storage system and to compare and analyze the effects of rainwater control, waterlogging prevention and water quality improvement on the traditional airport flight area lawn (without the ecological lawn regulation and storage system) and the ecological lawn regulation and storage system under precipitation scenarios with return periods of 5a, 10a, 20a, 30a, 50a and 100a. The total duration of the simulation is 5 h, of which the first 2 h are the designed precipitation duration and the last 3 h are the recession duration [37].

4.1. Simulation Analysis of Runoff Control

The simulation shows that under the precipitation scenarios with return periods of 5a, 10a, 20a, 30a, 50a and 100a, the runoff flow of the traditional airport flight area lawn is significantly greater than that of the ecological lawn regulation and storage system with different return periods, and the rainwater control rate ranges from 19.06% to 30.39%. With the addition of the ecological lawn regulation and storage system, the highest rainwater control rate is seen with the 5-year return period, reaching 79.79%. Although the rainwater control rate decreases with an increase in the return period, it still reaches 67.25% with the 100-year return period (Figure 5). The ecological lawn regulation and storage system has a significant and stable effect on runoff control in the airport flight area with different return periods.

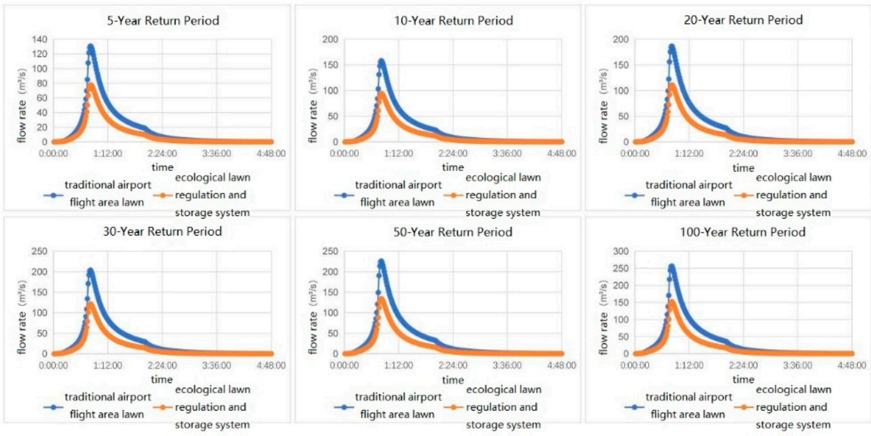

Figure 5. Comparison of simulated runoff with different return periods.

4.2. Simulation Analysis of Waterlogging Prevention

The simulation shows that the addition of the ecological lawn regulation and storage system has a certain control effect on airport flood control and drainage. Under the precipitation scenarios with return periods of 5a, 10a, 20a, 30a, 50a and 100a, the total ponding volume of the traditional airport flight area lawn is 5890 m^3, 19,411 m^3, 41,757 m^3, 57,708 m^3, 80,572 m^3 and 115,568 m^3, respectively. With the addition of the ecological lawn regulation and storage system, the total ponding volume is 1494 m^3, 6578 m^3, 14,905 m^3, 20,691 m^3, 29,014 m^3 and 42,625 m^3, respectively. The reductions in rainwater ponding volume with different rainfall intensities are different, and the largest reduction is with the 5-year return period, reaching 74.63%. As the rainfall intensity increases, the reduction in ponding volume gradually decreases by 74.63%, 66.11%, 64.31%, 64.15%, 63.99% and 63.12%, respectively. Compared with that of the traditional airport flight area lawn, the average ponding duration with the addition of the ecological lawn regulation and storage system is reduced by 42.6 min at most (Table 2). The ecological lawn regulation and storage system is able to effectively reduce the total ponding volume and the ponding duration in the airport flight area, thus achieving the effect of alleviating waterlogging.

Table 2. Comparison of simulated waterlogging with different return periods.

Rainfall Reappearing Period (a)	Ponding Duration (min)		Total Ponding Volume (m^3)	
	Traditional Airport Flight Area Lawn	Ecological Lawn Regulation and Storage System	Traditional Airport Flight Area Lawn	Ecological Lawn Regulation and Storage System
5	17.4	2.88	5890	1494
10	27.6	3.3	19,411	6578
20	36	5.1	41,757	14,905
30	40.8	6.18	57,708	20,691
50	45.6	7.8	80,572	29,014
100	52.2	9.6	115,568	42,625

4.3. Simulation Analysis of Water Quality Improvement

The simulation shows that under the precipitation scenarios with return periods of 5a, 10a, 20a, 30a, 50a and 100a, the addition of the ecological lawn regulation and storage system is able to remove some of the pollutants in the airport flight area. The reduction rates of TSS, COD, TN, TP and other indicators are used to evaluate the optimization effect of low-impact development on the rainwater runoff pollution. The reduction rate of the TSS discharge amount is 44.66%; the reduction rate of the COD discharge amount is 44.77%; the reduction rate of the TN discharge amount is 44.77%; and the reduction rate of the TP discharge amount is 44.83% (Figure 6). The ecological lawn regulation and storage system is able to effectively alleviate the initial rainwater runoff pollution.

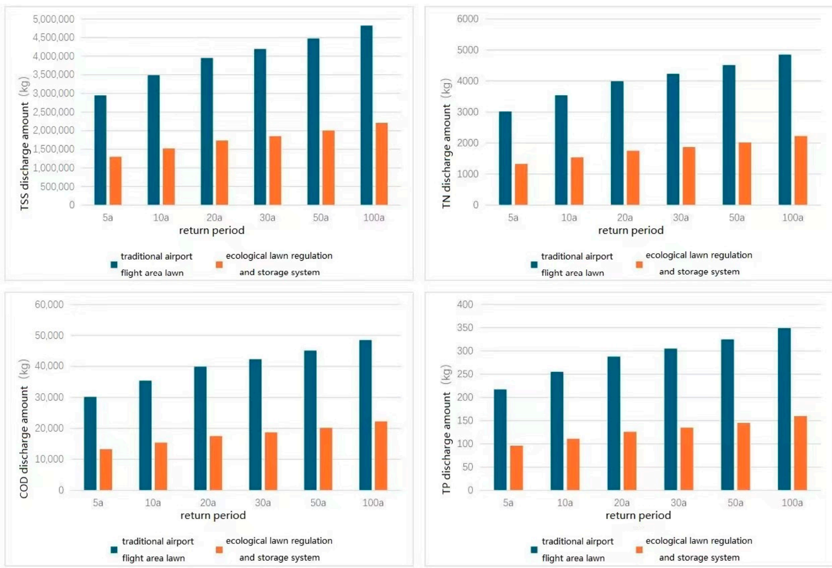

Figure 6. Comparison of simulated pollution discharge amounts with different return periods.

5. Conclusions

Reference [2] applied the concept of the sponge city to airports, combined with low-impact development facilities, to simulate the addition of permeable paving facilities. The proportion of pipe overload after the use of permeable paving facilities was 13–76% lower than that of nodes without permeable paving facilities, and the overload ratio of pipe segments decreased by 15.99–85%, indicating that the method can effectively control the internal flooding of the airport caused by node overload and pipe segment overload. Reference [30] adopted LID facilities for the design of sponge airports. After the construction of LID facilities, the maximum reduction in total runoff volume was 74%; the accumulation time was delayed by up to 16 min; the number of overflow nodes in the airport flight area decreased by 13.1; and the number of overloaded pipe segments decreased by 20.4%. Reference [38], taking the sponge system of Daxing Airport as an example, established a stormwater management model (SWMM) based on rainfall runoff data to simulate the hydrological process under different combinations of sponge facilities. The total control rate of rainwater reached 79%, and the reduction rate of the overflow volume reached 10.6%, showing obvious effects on peak cutting and peak delay.

This paper utilizes the large area of lawn around the traditional airport flight area in combination with gray facilities to construct an ecological lawn detention system. During light rain, by planting fine-rooted lawns, the surface runoff resistance is first increased, and the surface runoff is reduced. Then, by setting up detention channels, a physical separation is made between the pavement and the large area of lawn, discharging surface runoff from the rapid runway. The top of the detention channel is equipped with a filter net to reduce the pollution of the initial runoff of rainwater. The inside of the detention channel is composed of permeable bricks and water level sensors, which are used to capture the water level changes inside the detention channel and provide feedback to the intelligent terminal, and after the rain, the retained rainwater is slowly released to the surroundings for a long time through the permeability of the permeable bricks. During moderate rain, the water level sensor in the detention channel transmits the rate of water level rise to the intelligent terminal in real time. When the rate of water level rise is too fast, the intelligent terminal opens the intelligent valve to discharge rainwater into the water storage module through the overflow pipe. The water storage module also stores surface runoff, and it is set in an underground area beneath a concave ground surface, with coarse sand and large stones on top to reduce the phenomena of clogging and weed growth in traditional grass ditches. After the rain, the rainwater in the water storage module is purified and reused for lawn irrigation. During heavy rain, the water level sensor and intelligent terminal identify when the detention channel and water storage module cannot bear the total amount of rainfall, and after the detention channel and water storage module are full, the intelligent valve is opened, and the overflow rainwater is quickly discharged through the drainage pipe.

The ecological lawn detention system designed in this article significantly improves runoff control and flood prevention in the airport flight area. The rainwater control rate can reach 80%, and the accumulation time can be reduced by up to 42.6 min. In addition, by designing the ecological lawn detention system in the flight area, it fills the gap in the control of runoff pollution and rainwater reuse in the airport flight area using LID facilities. The filter net and rainwater purifier designed in the detention system can reduce the reduction rate of TS, COD, TN and TP by about 45%, and the water storage module designed in the detention system can store 24,000 cubic meters of water that can be recycled and utilized.

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