

Article

Analysis of Flooding Adaptation and Groundwater Recharge After Adopting JW Ecological Technology in a Highly Developed Urbanization Area

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Abstract: The relationship between Taiwan's groundwater resources recharge strategy and flood disasters is significant. The adaptation strategies of traditional urbanization areas simulate the spatial distribution of permeable pavements under different rainfall intensities that affect surface runoff and infiltration. Since there are many parameters of the Stormwater Management Model set in different low-impact development modules, this study refers to transform the inundation to groundwater recharge. In this study, we simulated the spatial distribution multi-advantages of the JW ecological technology under short-duration intense rainfall events. The results show that the application of JW ecological technology can effectively increase groundwater resources by 64.1% through infiltration and reduce economic losses by about NTD 1.25 million under the rainfall event of 112 mm/1 h. The infiltration replenishment amount was about 61%, which could reduce the economic loss of NTD 4.4 million under the rainfall event of 350 mm/6 h. Thus, applying JW ecological technology in a highly developed urbanization area can effectively reduce surface runoff and economic losses. At the same time, the issue of water resources was adapted by the groundwater recharge.

Keywords: land adaptation strategies; Storm Water Management Model; low impact development; JW ecological technology



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1. Introduction

The annual average rainfall in Taiwan is more than 2500 mm, which is 2.6 times more than the world average. However, it is distributed unevenly and is high in summer. Urbanization has caused an increase in impermeable areas in cities, population concentration, and a significant change in land utilization. Forests and agricultural coverage have decreased, and as the precipitation infiltration rate and groundwater resources goes down, the surface runoff increases. This increased runoff overloads the drainage system and may lead to inundation in low-lying lands. In rapid urban development, drainage system planning is spatially and financially restricted. Alessandro Pezzoli et al. [1] opined that the natural phenomena must be followed with a continuous data collection. The results can be applied to engineering practice through statistical research. Engineering from the database and model results also explores whether existing constructions will be affected by the extreme weather event caused by climate change, such as the increase in average sea level, frequent heavy rainfall, drought, and landslide events. According to Chung-Wen Lee [2], the JW ecological technology of permeable pavement emphasizes laying a considerable thickness of gravel under the artificial pavement. With its water storage and water activation of the soil, its load capacity can be applied to the road pavements to withstand various vehicles (Chen, Jui-Wen) [3]. The surface of permeable pavement has about 100 holes per square meter, and air-conditioning water pipes are used to provide rainwater penetration. Jeremy C. Tredway et al. [4] indicated that low-impact development is a method of stormwater management, which detains runoff near its source by preserving natural landscape features and limiting

impermeability. Their study also shows that the technique of low-impact development can reduce runoff of the maximum flow generated by stormwater. Muhammad Shafique et al. [5] reported that under this circumstance, green roofs offer many benefits, including the simulation of on-site rainwater management with natural hydrological conditions of urban areas, which can retain large amounts of rainwater for extended periods and delay peak discharges. However, Tredway and coworkers also referred to fully developed areas where many old building structures may have already used vegetative roofs. Urbanization leads to increased runoff, leading to erosion, floods, and deterioration of the health status of river ecosystems. Although best management practices are widely adopted to control stormwater and runoffs, the low-impact development plan has been proposed as an alternative by utilizing a dispersed design to control stormwater and better simulate the natural flow. Jennifer et al. [6] adopted the rainwater management model from the US Environmental Protection Agency (USEPA) to quantify the benefits of stormwater management and observed that rainwater harvesting can reduce runoff by 20% in semi-arid areas, while long-term simulations revealed that runoff was significantly reduced for heavy rainfall areas [7]. Overall, these results show that the cities in the U.S. and individual households can benefit from rainwater harvesting as a means of harnessing rainwater and alternative water source. On the other hand, the most applicable scope of low-impact development facilities is on single development basis. Hence, if land-use planning and detailed planning are included during the proposal stages, the overall benefits are more significant (Yu, J.-Y.) [8]. Donggeun Kwak et al. [9] observed that the combination of low-impact development facilities also affected runoff characteristics and that the total runoff and peak runoff were significantly reduced by increasing retention capacities and permeable areas. Integrated planning can be carried out by utilizing professional help in groundwater conservation, such as hydrological analysis, flood potential analysis, etc., in conjunction with land use, allocation of runoff, etc. set by urban planning, and combining water and land features (Chang, H.-S. et al.) [10]. Current improvements on the water environment are only determined by statistical analysis of spatial clustering as a preliminary discussion for regional water environment construction scale and functional positioning with a hope to provide planners basic knowledge that combines water conservation-related fields as a means for adapting responses in future urban space development for the water environment. In their study, Zheng Peng et al. [11] observed that permeable paving in high-density residential areas is the best option for a single measure of low-impact development. The mix of permeable paving and green roofs is the best composition for low-impact development. Likewise, Pellicani et al. [12] emphasized the importance of loss caused by floods, using different rainfall pattern parameters (such as rainfall, land use, permeability, and roughness), and hydrological models to obtain risk curves to benefit related units and determine appropriate risk mitigation measures. Chandana et al. [13] found that low-impact development practices, such as rainwater harvesting, green roofs, and permeable paving, can be used to transform existing infrastructures and reduce runoff and peak flow in highly urbanized areas. Therefore, the objective of this study was to analyze and improve the adaptation system in cities for the prevention of inundation and groundwater recharge. Hsiao-Min Chang [14] researched that the water environment cannot form a system with a single base, so the new urban storm management concept requires land development and runoff control at the same time. Ho, Ming-Chin et al. [15] researched and put forward four strategies to increase flood detention space in urban areas, including public facilities, legal open space, the increase of rainwater storage facilities in buildings, and the change of land use zoning. Chao-Hsien Liaw et al. [16] proposed that LID is a feasible and cost-effective alternative designed in a very environmentally sensitive way, which can protect streams, wetlands, forests, and habitats and conserve energy. Hsueh-Sheng Chang et al. [17] research shows that the development of water conservancy and agricultural land has caused the loss of water conservation and culvert function land, and also caused the impact of the water environment, which may cause floods, resulting in changes in runoff and the trend of affecting the overall water environment. Yung-Yun Cheng et al. [18]

proposed that two types of pavements were installed, a porous asphalt bicycle lane and a permeable interlocking concrete brick pedestrian walkway. The objectives are to assess (a) the stormwater runoff control performance, such as peak runoff and volume reduction; (b) the time variation of infiltration rates of pavements. Jen-Yang Lin et al. [19] found that with an increase in rainfall, the water retention rate decreased because the storage capacity was limited. The thickness of the storage layer is an essential parameter, and it offers the temporary storage space of rainwater for infiltration. In this study, we used the stormwater management model to examine the problems of the existing drainage system in the study area and combined it with the JW ecological technology to ameliorate the urban system and achieve the maximum retention of the peak discharge and increase the groundwater recharge. Therefore, the infiltration and storage of rainwater on-site are applied LID design concept, turning impervious pavements into pervious pavements. The study area selected Taishan District, New Taipei City, for the case study, simulating and comparing the effects of the regional groundwater recharge and economic losses affected by implementing the JW ecological technology.

2. Methodology

This study applied the stormwater management model (SWMM) as the primary analysis tool, and Taishan District, New Taipei City, is the case site for a numerical simulation of the drainage system. By inputting different extreme precipitations, and by making use of the runoff module in SWMM, the calculation results in the inflow hydrograph of the man-hole of storm sewer system dynamically compute the pipeline water supply, demonstrate the situation of the overflow, and as a result, lead to a better understanding and review of the drainage system problems. Furthermore, the research also examined whether the JW ecological technology has a positive impact on the groundwater resources recharge and the drainage by joining the melioration project in the simulation system.

2.1. Collection of Related Data

Alessandro Pezzoli et al. [1] research conclusion emphasizes that natural phenomena must start from continuous collection of data. Any analysis is based on the collection, storage, and processing of natural variable data (tide level, rainfall height, waves, currents, etc.) in order to deal with statistically linking phenomena to the probability of occurrence. We collected the 5 m × 5 m digital elevation models, the planning report of the storm sewer system, the urban planning report in the research region, and the Operating Manual of Water Environment Low-Impact Development Facilities and Case Evaluation Plan from the Construction and Planning Agency, Taiwan. The existing pavement block distribution was used as a reference to manually designate each sub-catchment area, and then use geographical information system in the 5 m × 5 m digital elevation models to calculate the slope and direction of the tilt field, and analyze the flow direction based on the results.

2.2. Stormwater Management Model

The stormwater management model is the USEPA Publicly released software that is widely used for planning, analysis, and design in urban or non-urban areas. The SWMM can be applied to urban stormwater runoff drainage system, mixed-flow sewer system, and other drainage systems. At present, the stormwater management model is used by the USEPA for the planning, analysis, and design of floods, sewers, sewers, and other drainage systems in urban areas around the world. It considers factors, such as groundwater, surface infiltration, and evaporation. The new version also includes calculation modules for low-impact development facilities, such as ecological reservoirs, infiltration ditches, porous walkways, awnings, and grass ditches for runoff simulation.

2.3. JW Ecological Technology

The “JW Ecological Technology” is regarded as the “breathing earth-colored clothing”, also known as the breathing pavement, as shown in Figure 1. Chen, Jui-Wen [3] invented

this concept to change the impervious artificial pavement, such as roads, sidewalks, and squares in the city, into the pavement that is highly permeable and can circulate convective air above and below ground to form a natural earth “air conditioning system”, which meets the requirements of the guidelines for promoting the construction of sponge cities. The gravel layer under the road using the profile of JW ecological construction is also presented in Figure 1. When heavy rain hits, a large volume of rainwater can quickly enter the gravel layer and the graded layer through the water pipe, and these two layers form a temporary underground reservoir. The water retention rate of the base layer is six times that of the original permeable pavement, and it can reach 15 times or more after adding the JW hollow ecological ball, which can make up for the lack of natural permeability of the soil and allow the soil to slowly absorb and supplement groundwater. Thus, floods can be avoided. The JW ecological technology can effectively prevent flood and drought disasters and enhance the utilization and management of water resources. According to the actual measurement, during heavy rain, there is still no water and runoff on the JW road surface, and the water permeability reaches 1250 mm per hour.

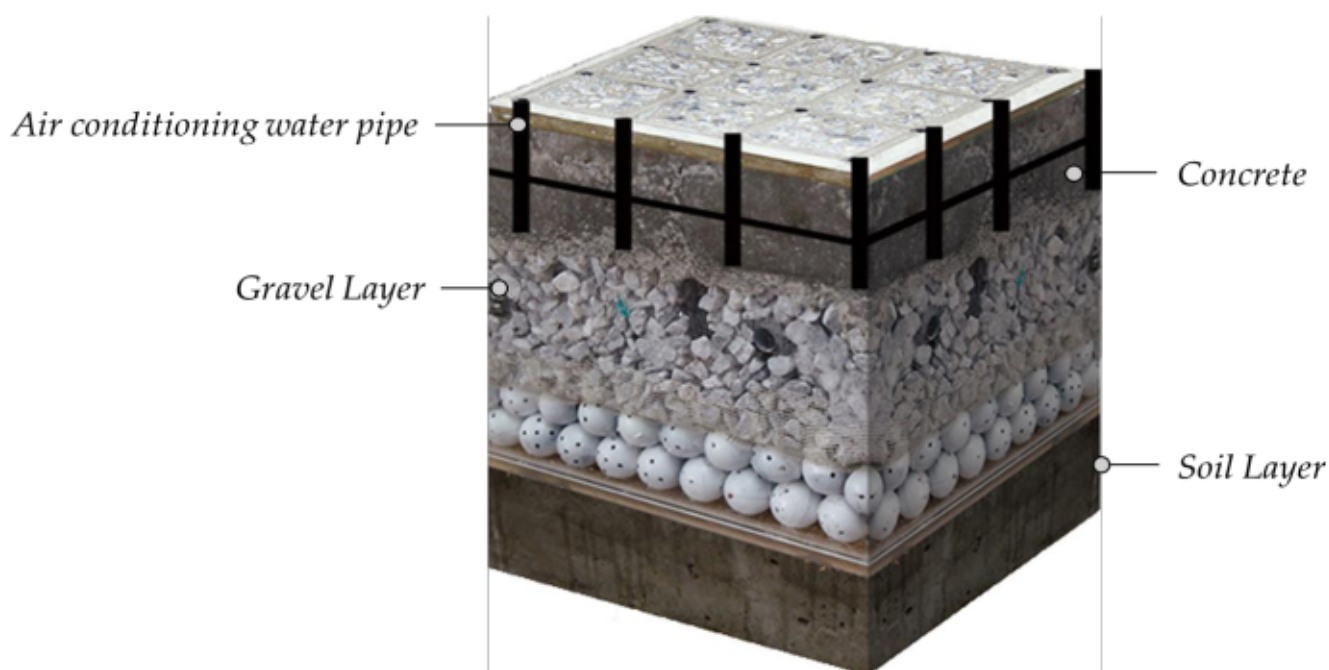


Figure 1. The profile of JW ecological technology. Modified from: CHYI SHYANG CO., LTD. [20].

2.4. Establishment of the Runoff Coefficient

There are quite a few factors that may influence the runoff coefficient. These natural and artificial conditions may include the rate and duration of precipitation, surface condition, ground gradient, flow distance, geography, groundwater level, and above-ground structure, etc. Especially, the precipitation duration and the surface condition are the most critical factors. The contents of the stormwater management model user’s manual show the planning of the rainwater channel system, and consider the impervious surface area, which varies according to the type of land use subdivision of the urban plan. When designing, related parameters can be chosen according to the characteristics of the area (Table 1). Taishan District, New Taipei City, belongs to the high-urbanization area, and according to the current survey, most of it is used for cultivation, the impervious surface area was used as the area of study.

Table 1. The vertical construction parameters of the different impermeability zones.

Layer	Content	Current Pavement	General Permeable Pavement	JW Ecological Technology
Surface	Roughness	0.01	0.02	0.012
	Slope	0.2%	0.2%	0.2%
Pavement	Thickness	500 mm	500 mm	500 mm
	Void Ratio	0.03	0.12	0.21
	Permeability	15 mm/h	150 mm/h	1250 mm/h
Soil	Thickness	45 mm	45 mm	45 mm
	Porosity	0.05	0.15	0.3
	Field Capacity	0.08	0.08	0.08
Storage	Thickness	1000 mm	1000 mm	1000 mm
	Void Ratio	0.23	0.35	0.43
	Seepage Rate	0 mm/h	0 mm/h	150 mm/h
	Clogging Factor	0	0	0
Underdrain	Flow Coefficient	0	0	0

Data sources: Low-impact development manual [21] and CHYI-SHYANG CO., LTD. [20].

3. Case Study

3.1. Overview of the Study Area

The study site is located in the eastern part of Taishan District, with a high urbanization area of 0.5441 km². The terrain of the Taishan District is slightly high in the west and low in the east, and the altitude of the simulation area is between 3.46 and 4.92 m. The research site is also located in a metropolitan area with a high proportion of housing estate area. The JW ecological technology can effectively reduce urban surface runoff if an intense rainfall event of short-duration occurs. The plains formed by the river alluvium in the eastern region have the lowest terrain. The simulated area is also a very flat terrain. Its elevation and location are presented in Figure 2. To the east, only the local drainage ditch flows through. No large rivers flow through this area.

3.2. Drainage System and Rainfall Data

Since the rainwater channel system has been installed in the study area, the system concentrated on the existing blocks and the gutters of the road system in the nearby local area to determine the drainage area (shown in Figure 3). After some flooding events, the flooding project was examined and found that in the past 10 years, there have been no serious typhoon disasters and serious casualties in the study area, and only local inundations have occurred. For the simulation of rainfall events, we referred to the historical precipitation records of the Wugu Station of Taiwan's Central Meteorological Bureau, which is the nearest to the base center. They are respectively 112 mm/1 h and 234.5 mm/3 h. In addition, the extreme events caused by global climate change, lead to frequent heavy rains, and in the future, groundwater resources will become increasingly serious, simultaneously. The quantitative precipitation simulation scenario of the 350 mm/6 h, using empirical methods, was based on historical flooding and rainfall data to develop a flooding scenario as rain in the stormwater management model of this study.

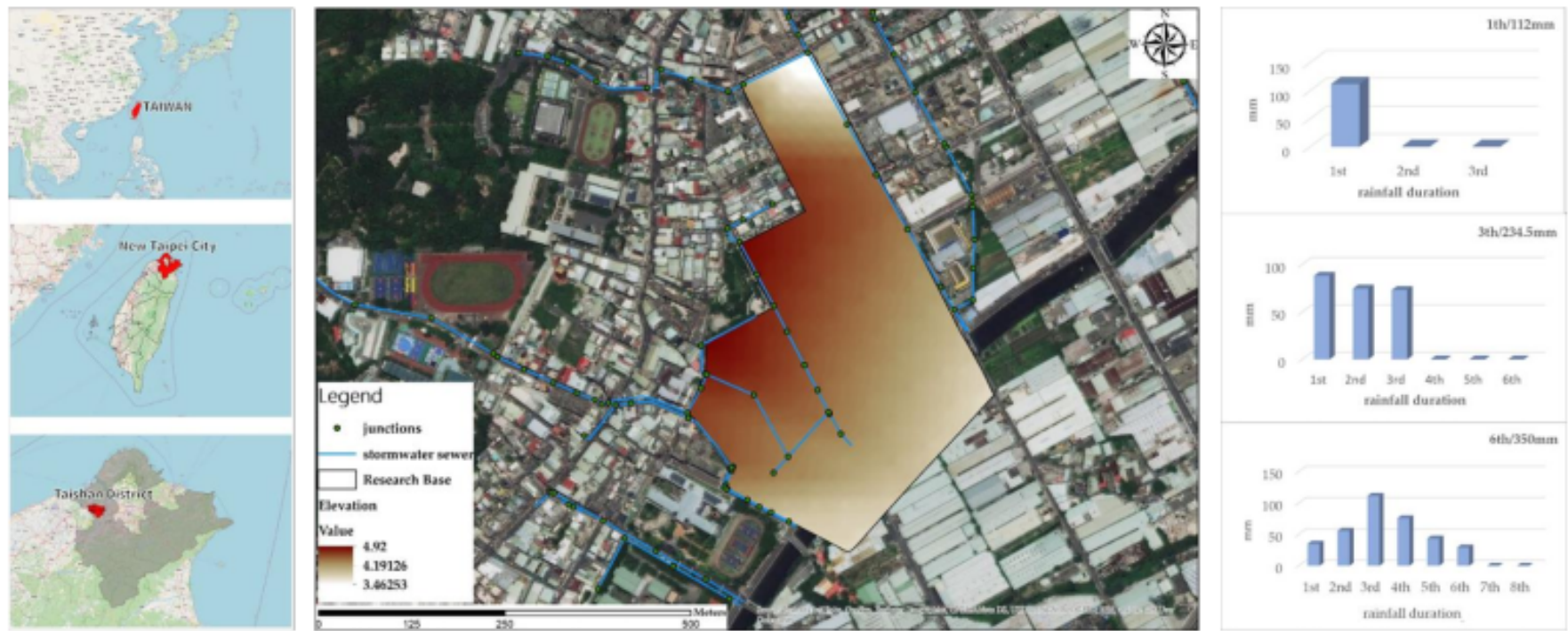


Figure 2. Schematic diagram of elevation and the main stormwater sewer.



Figure 3. Establishment of the drainage system in the study area.

3.3. Establishment of the Drainage System

To simulate the drainage system in the study area, we first decided the watershed division of this region and then collected the information about the drainage trunk lines and the gully holes. According to the actual field investigation of this research, it is found that the current pavement of the base road is porous asphalt pavement, and the original porous asphalt pavement is redesigned to JW ecological technology to facilitate subsequent simulation research. This study area contained 21 parts of the watershed. This research mainly drew the sub-catchment unit based on the street profile, the elevation of the base, and the direction of the main drainage system, as shown in Figure 3. The study area of land use category is almost the housing estate and the commercial district (about 45.7% of total area). The road area that adopts JW ecological technology is about 25.9% of the total study area. The park and green land is 28.4% of the total study area. The drainage pipeline system and the inflow manhole contribute to the storm sewer system. To cooperate with stormwater management model calculation, this research converted the data of the storm sewer system, including the shape of the trunk section, length of the trunk line, gradient, and Manning's coefficient of roughness, into numbered nodes and arteries (detailed parameters of sub-catchment refer to Appendix A).

3.4. Stormwater Management Model Parameter Sensitivity Analysis

3.4.1. The Sensitivity Analysis Formula

The sensitivity analysis of the study referred to Shu-Yu Lin. [22] using the Morris test method to detect the sensitivity analysis of stormwater management model hydrological model parameters. The Morris test method selects the variable X_i in each parameter, and the remaining parameter values are fixed. The variable X_i is randomized within a reasonable range change, using the objective function $y(x) = y(X_1, X_2, X_3 \dots X_n)$ simulated by X_i , and then E_i is used to determine the degree of influence on the simulation result after the parameter changes.

$$E_i = \frac{(y^* - y)}{\Delta_i} \quad (1)$$

Formula parameters:

y^* = simulation result after parameter change

y = simulation result before parameter change

Δ_i = the change range of parameter I

The modified Morris test method was used to analyze the sensitivity of parameters. This method uses a fixed percentage change of the independent variable, and its formula is

$$SN = \sum_{i=1}^{m-1} \frac{(Y_{i+1} - Y_i)/Y_0}{(P_{i+1} - P_i)/100} / m \quad (2)$$

Formula parameters:

SN = the sensitivity discrimination factor

Y_0 = Initial value after parameter calibration

Y_i = simulates the i -th output value

Y_{i+1} = simulates the output value of the $I + 1$ th time

P_i = the percentage change in the i -th simulation parameter relative to the parameter after the calibration

P_{i+1} = simulation $i + 1$ th simulation parameter relative to the percentage change of the initial parameter after calibration

m = number of simulations.

3.4.2. The range of Parameter Value

The application of the permeable pavement in this study area does not have actual measurement data for verification; therefore, the sensitivity analysis of the pending parameters of the low-impact development technology model should be carried out before the establishment of the SWMM in the case area. The following contents summarize the description of important parameters of permeable pavement in the SWMM simulation. The reference source is the EPA SWMM user manual and LID Design Guide.

(1) Surface Slope

The slope of a roof surface, pavement surface, or vegetative swale (percent). Use 0 for other types of LIDs.

(2) Thickness

The thickness of the pavement layer (inches or mm). Typical values are 4 to 6 inches (100 to 150 mm).

(3) Void Ratio

The volume of void space relative to the volume of solids in the pavement for continuous systems or for the fill material used in modular systems. Typical values for pavements are 0.12 to 0.21. Note that porosity = void ratio / (1 + void ratio).

(4) Permeability

Permeability of the concrete or asphalt used in continuous systems or hydraulic conductivity of the fill material (gravel or sand) used in modular systems (in/h or mm/h). The permeability of new porous concrete or asphalt is very high (e.g., hundreds of in/h), but can drop off over time, due to clogging by fine particulates in the runoff (see below).

(5) Thickness (or Barrel Height)

This is the thickness of a gravel layer or the height of a rain barrel (inches or mm). Crushed stone and gravel layers are typically 6 to 18 inches (150 to 450 mm) thick, while single-family home rain barrels range in height from 24 to 36 inches (600 to 900 mm).

(6) Void Ratio

The volume of void space relative to the volume of solids in the layer. Typical values range from 0.5 to 0.75 for gravel beds. Note that porosity = void ratio / (1 + void ratio).

(7) Seepage Rate

The rate at which water seeps into the native soil below the layer (in inches/h or mm/h). This would typically be the Saturated Hydraulic Conductivity of the surrounding sub-catchment if Green-Ampt infiltration is used or the Minimum Infiltration Rate for Horton infiltration. If there is an impermeable floor or liner below the layer, then use a value of 0.

This study used the modified Morris test method to analyze the sensitivity of the parameters in the stormwater management model. The various hydrological and hydraulic parameters were changed within the 10% adjustment range, and the values were -50% , -40% , -30% , -20% , -10% , 10% , 20% , 30% , 40% , and 50% , when one of the parameters was changed, and the other parameters remain fixed. The sensitivity of each parameter was analyzed to the peak flow and outflow volume under the six-hour delay of 350 mm rainfall at the Wugu rainfall station in New Taipei City. For the sensitivity analysis range of permeable pavement with built-in functions in the stormwater management model, the reference range for parameter values were adopted from the stormwater management model user's manual Version 5.1. [7], Low-Impact Development User manual [12], and other manuals and specifications, and the reasonable range of its parameters were selected. The undetermined parameters were changed within a reasonable range, and then the simulation output results were used to analyze the sensitivity of the undetermined parameters. The parameter value range of the stormwater management model del permeable pavement is mentioned in Table 2.

Table 2. The value range of permeable pavement parameter of the stormwater management model.

Parameter	Current Pavement	Permeable Pavement	JW Ecological Technology
Surface Layer			
Roughness	0.005~0.015	0.01~0.03	0.006~0.018
Slope	1~2 (%)	1~2 (%)	1~2 (%)
Pavement Layer			
Thickness	50~60 (mm)	50~60 (mm)	50~60 (mm)
Void Ratio	0.015~0.045	0.2~0.4	0.105~0.315
Permeability	5~8 (mm/h)	75~225 (mm/h)	625~1875(mm/h)
Storage Layer			
Height	500~1500 (mm)	500~1500 (mm)	500~1500 (mm)
Void Ratio	0.03~0.09	0.175~0.525	0.215~0.645

3.4.3. Results

The simulated output results of parameter changes were obtained by the Morris test method to determine the sensitivity values of the undetermined parameters and were divided into four categories according to the sensitivity values of the parameters (presented in Table 3).

Table 3. The attributes of the sensitivity values.

SN	Attributes
$SN = 1$	High sensitivity parameters
$0.1 \leq SN < 1$	Sub-sensitivity parameter
$0.05 \leq SN < 0.1$	Medium sensitivity parameter
$0 \leq SN < 0.05$	Low sensitivity parameters

Source: Shu-Yu Lin [22]; summary of this research.

The sensitivity of the stormwater management model permeable pavement parameters was analyzed using the six-hour duration of 350 mm rainfall at Wugu Station in New

Taipei City. The analysis results are categorized into peak flow of the flood and outflow volumes. The results are shown in Tables 4 and 5. For the sensitivity of the outflow volume, thickness of the storage layer is the sub-sensitive parameter, the void ratio in storage layer is the medium-sensitive parameter, and the remaining are low-sensitive parameters. For the sensitivity of the flood peak discharge, thickness in storage layer is also the sub-sensitive parameter, and the void ratio in the storage layer is the medium-sensitive parameter. The thickness and void ratio of the storage layer is a slight sensitive reaction. The standard operating procedures and the profile construction of general permeable pavement and JW ecological technology are consistent. The following simulation results have been validated.

Table 4. SN value and sensitivity analysis of the stormwater management model permeable pavement parameters to outflow volume.

Parameter	Current Pavement	Permeable Pavement	JW Ecological Technology	Correlation	Sensitive
Surface Layer					
Roughness	0.00098	0.00049	0.00087	-	low
Slope	0.00013	0.00013	0.00013	-	low
Pavement Layer					
Thickness	0.00713	0.00713	0.00713	-	low
Void Ratio	0.039	0.00975	0.00557	-	low
Permeability	0	0	0	non	low
Storage Layer					
Thickness	0.1248	0.1248	0.1248	-	sub
Void Ratio	0.09952	0.06635	0.08151	-	medium
Seepage Rate	0	0	0	non	low

Table 5. SN value and sensitivity analysis results of the stormwater management model permeable pavement parameters to flood peak discharge.

Parameter	Current Pavement	Permeable Pavement	JW Ecological Technology	Correlation	Sensitive
Surface Layer					
Roughness	0.0182	0.0091	0.0015	-	low
Slope	0.00049	0.00049	0.00049	-	low
Pavement Layer					
Thickness	0.00823	0.00823	0.00823	-	low
Void Ratio	0.03644	0.00911	0.01594	-	low
Permeability	0	0	0	non	low
Storage Layer					
Thickness	0.1091	0.1091	0.1091	-	sub
Void Ratio	0.1447	0.0965	0.0117	-	medium-sub

4. Discussion

4.1. The Inundation Results

As shown in Table 6, the different short-duration intense rainfall events simulate the highly developed urban area based on the current drainage system and land use. The current situation of the road and parking lot is porous asphalt. The traditional housing estate and the commercial district increase the impervious area. The simulation without any permeable pavement separately results in 93,774 m³ (a peak of about 9.33 cm), 188,352 m³ (a peak of about 16.52 cm), and 270,360 m³ (a peak of about 17.65 cm) of surface runoff. According to the simulation results, a short-duration intense rainfall can cause severe flooding problems in the study area that urbanized for a long time. Application of JW

ecological pavement of the leading-edge technology can reduce the damage and economic losses caused by the flood. Besides, it also increases the infiltration and recharges the groundwater resources in an urbanized area that needs to be developed sustainably.

Table 6. Comparison of the hydrographical simulation results of different short-duration intense rainfall events.

Results	Scenario Events		
	112 mm/1 h	234.5 mm/3 h	350 mm/6 h
Peak (cms)	9.33	16.52	17.65
Total Volume (m ³)	93,774	188,352	270,360

4.2. Economic Loss Caused by the Inundation

According to Lamb, R et al. [23], the flood risk assessment provides valuable information about the expected annual consequences of floods, but does not provide a large number of simultaneous flood exposures, and this can have devastating consequences for humans and the economy. Shan, C.C [24] suggested that when establishing a flooding hazard risk map, the data on the relationship between flooding depth, area, and loss must also be emphasized. The economic loss, due to floods, was analyzed by Ling-Fang Chang [23] considering the potential risks of various types of buildings, and using the flood loss curve method to estimate the direct economic loss of the residential areas into three aspects: (1) General home interior decoration, (2) mechanical and electrical equipment and (3) motor vehicle losses. The growth situation uses the socio-economic database and the construction management data of Taiwan to estimate the curve of ordinary household flood loss, as well as to establish the flooding depth-economic loss map. This method first calculates the loss value of a regional unit in each land use classification by using the average number of households in each category and the comparability of flood height and household losses. According to Ling-Fang Chang [25], different types of buildings may suffer damage, due to flooding at varying degrees, and the most serious damages usually occur in basements or underground spaces. As a result, the type and damage of the building can be divided into two categories (shown in Figure 4). In addition, damage to the building caused by flooding can also be of two types, namely, the interior decoration and the public facilities. Generally, houses on lower floors may suffer more severe internal damage, while public facilities in community houses and apartment buildings suffer overall severe damage. Based on the above-mentioned references, the calculation rules mentioned in the above-mentioned reports were used to calculate the study area (including mainly the low-rise townhouses that do not belong to the urban planning area, most of which are low-rise townhouses). Based on the above calculation and research, the total loss caused by the sinking of 112 mm within one hour is NTD \$3 million, and the total loss caused by the sinking of 234.5 mm within three hours is NTD \$7.9 million, caused by 350 mm flooding for one day. The total loss within this period amounted to NTD \$9 million.

4.3. Multi-Targets Analysis

(1) The 112 mm/1 h rainfall scenario

The permeable pavement element of the low-impact development controls module in the stormwater management model hydrological model was used to simulate the base under the 112 mm/1 h rainfall scenario compared with the current surface runoff (93,744 m³) of the study base. The total surface runoff volume was reduced by about 47,196 m³ (49.1%, shown in Figure 5), which also increased the infiltration area by about 14 hectares and improved the groundwater recharge. The current surface runoff of the base causes economic losses amounting to nearly NTD 3 million. After applying the general permeable pavement, the economic benefit can be reduced by about NTD 1,675,000 (44.2%). Compared with the original runoff in the 112 mm/1 h rainfall scenario, the total surface runoff volume can be reduced by about 33,624 m³ (64.1%) using the JW

ecological technology to simulate the base in the 112 mm/1 h rainfall scenario. The current surface runoff of the base causes economic losses amounting to nearly NTD 3 million. After applying JW ecological technology, its economic benefits can be reduced by approximately NTD 1.25 million (58.3%), which can effectively mitigate the negative impact of heavy rainfall. The summary comparisons of multi-targets are shown in Table 7.

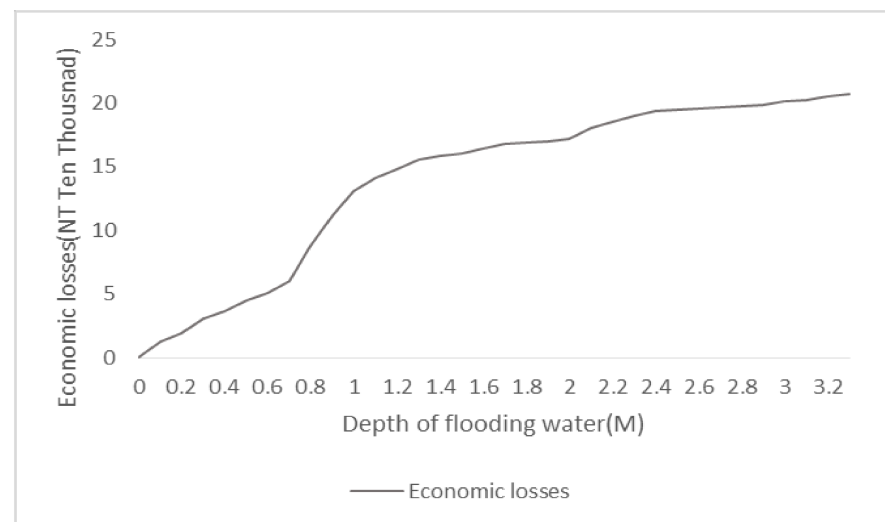


Figure 4. Flood damage estimation for residential area.

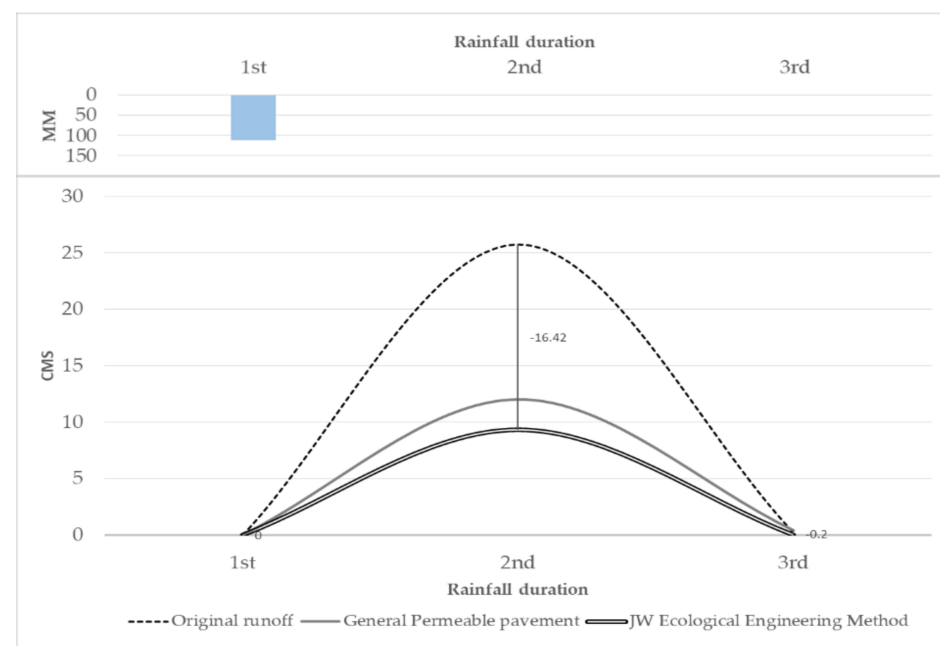


Figure 5. Simulation result for 1 h/112 mm.

(2) The 234.5 mm/3 h rainfall scenario

The 234.5 mm/3 h rainfall scenario was also compared with the current surface runoff (188,352 m³) of the base. The total surface runoff volume could be reduced by about 94,788 m³ (49.6%, shown in Figure 6), increased the infiltration area of about 14 hectares, and improved the groundwater recharge. The current surface runoff of the base causes an economic loss of nearly NTD 7.9 million economic losses. After applying general permeable pavement, the economic benefits can be reduced by about NTD 3 million

(62.0%). Compared with the original runoff in the 234.5 mm/3 h rainfall scenario, the total surface runoff volume can be reduced by about 70,920 m³ (62.3%) by using the JW ecological technology to simulate the base. The current surface runoff of the base causes an economic loss of nearly NTD 7.9 million economic losses. After applying JW ecological technology, its economic benefits can be reduced by approximately NTD 2.25 million (71.5%).

Table 7. Comparisons of multi-targets.

Scenario	112 mm/1 h	234.5 mm/3 h	350 mm/6 h
Reduction of the Inundation (equal to the recharge of the unconfined aquifer)			
Original Runoff	93,744 m ³	188,352 m ³	270,360 m ³
General Permeable pavement	47,196 m ³ (49.1%)	94,788 m ³ (49.6%)	140,616 m ³ (48%)
JW Ecological Technology	33,624 m ³ (64.1%)	70,920 m ³ (62.3%)	105,120 m ³ (61%)
Economic benefit (NTD)			
Original loss	3,000,000	7,900,000	9,000,000
General Permeable pavement	1,675,000 (44.2%)	3,000,000 (62.0%)	6,500,000 (27.8%)
JW Ecological Technology	1,250,000 (58.3%)	2,250,000 (71.5%)	4,400,000 (51.1%)

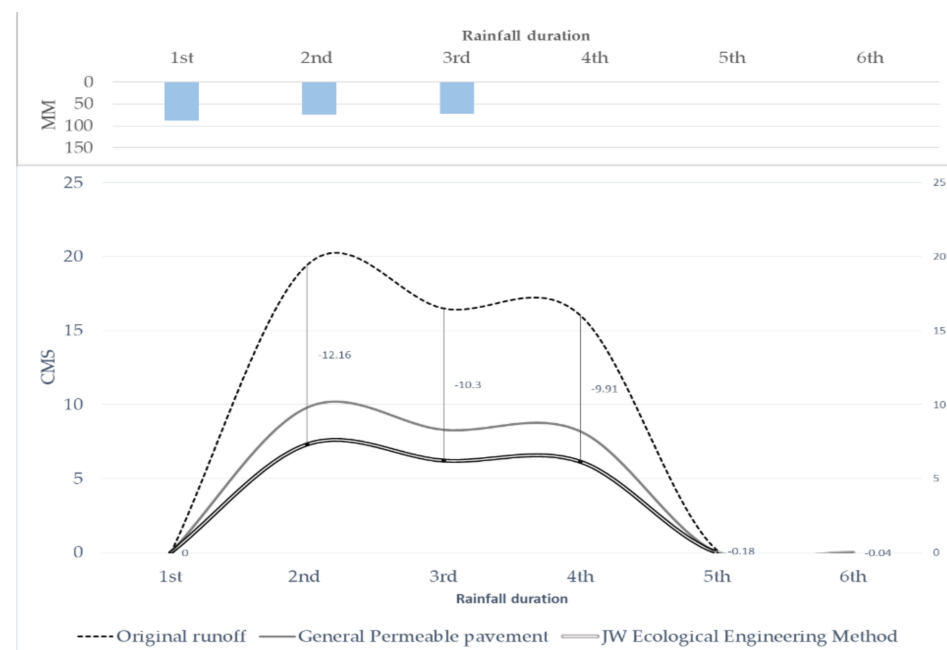


Figure 6. Simulation result for 3 h/234.5 mm.

(3) The 350 mm/6 h rainfall scenario

The 350 mm/6 h rainfall scenario also compared with the current surface runoff (270,360 m³) of the base. The total surface runoff volume could be reduced by approximately 140,616 m³ (48%, shown in Figure 7), increased the infiltration area by about 14 hectares, and improved the groundwater recharge. The current surface runoff of the base causes an economic loss of nearly NTD 9 million. After applying the general permeable pavement, the economic benefit was reduced by about NTD 600 500,000 (27.8%). Compared with the original runoff in the 350 mm/6 h rainfall scenario, the total surface runoff volume can be reduced by about 105,120 m³ (61%) using the JW ecological technology to simulate the base in the 350 mm/6 h rainfall scenario. The current surface runoff of the base causes

an economic loss of nearly NTD 9 million. After applying JW ecological technology, its economic benefits can be reduced by about NTD 4.4 million (51.1%).

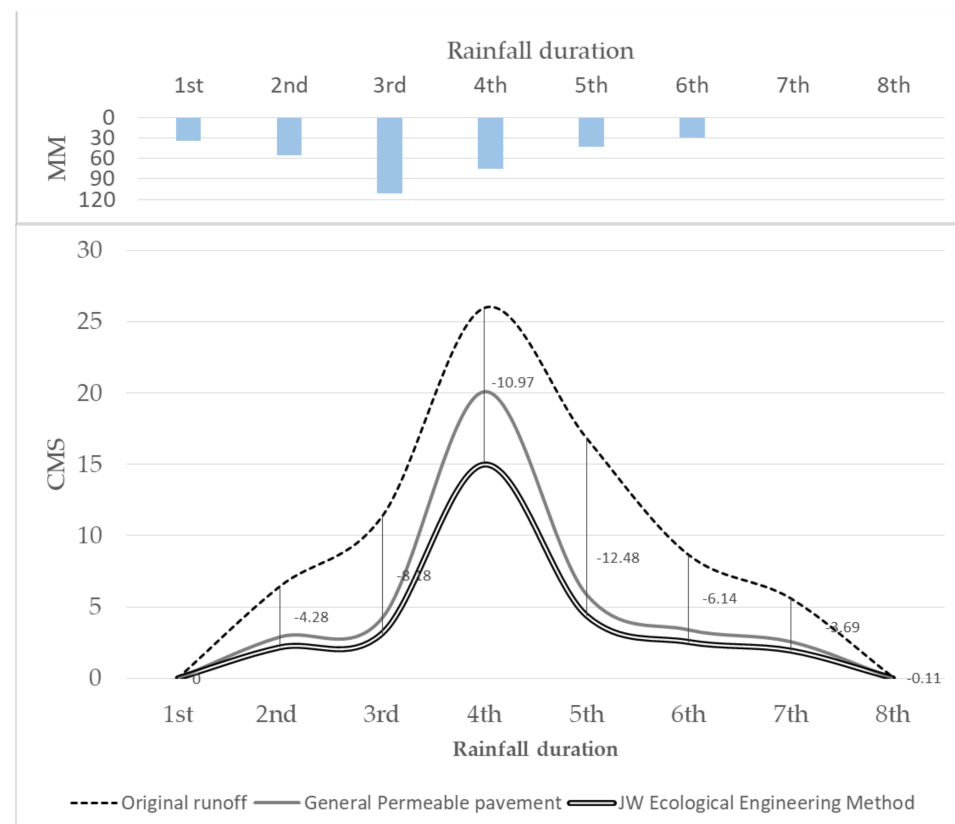


Figure 7. Simulation result for 6 h/350 mm.

5. Conclusions

In this study, the stormwater management model was combined with the general permeable pavement of low-impact development and JW ecological technology to simulate the variations of the surface runoff in a highly developed urbanization area. The flooding depth versus economic loss was used to calculate the benefits of the study area using general permeable pavement and JW ecological technology. The results of the research quantify the expected effects of different pavements in reducing surface runoff and increasing groundwater resources.

5.1. Groundwater Recharge in a Highly Developed Urbanization Area

The simulations of this study found that in three rainfall scenarios (112 mm/1 h, 234.5 mm/3 h, and 350 mm/6 h), the surface runoff was 93,744 m³, 188,352 m³, and 270,360 m³, respectively. The general permeable pavement reduced the surface runoff to less than 50% (48–49%), while the JW ecological technology reduced the surface runoff to more than 60% (61–64%) in the three rainfall scenarios. The results indicate that the JW ecological technology can increase groundwater recharge and simultaneously reduce surface runoff. The multi-benefits of JW ecological technology are also more than those of the general permeable pavement.

5.2. Economic Benefit

This research referred to the flood loss curve of Line-Fang Chang [23] to estimate the economic losses under the three rainfall scenarios at NTD 3 million, 7.9 million, and 9 million, respectively. Generally, general permeable pavements have an economic benefit of 62% and a minimum of 27.8% in flood-loss, while JW ecological technology has a maximum economic benefit of 71.5% and a minimum of 51.1% in flood-loss.

According to our results, applying JW ecological technology reduces surface runoff of highly developed urbanization areas, and is superior to general permeable pavements in terms of surface runoff reduction and economic benefits, with greatly increased ground-water resources and recharge. In the future, the JW ecological technology can be used in conjunction with other low-impact development facilities to sustainably share urban development and optimize flood control benefits.

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Appendix A

Table A1. Overview of stormwater management model (SWMM) sub-catchments parameters (refer to Figure 3).

Catchment No.	Category of Land Use	Area (ha)	Width (m)	Slope (%)	Sealed Surface-Impervious Area (%)	JW Implement Area (%)
S1	Housing estate	3.72	390	5	79	25.8
S1	Housing estate	2.24	200	5	79	27.6
S3	Housing estate	1.95	109	5	79	29.7
S4	Housing estate	1.69	178	5	79	33.4
S5	Housing estate	1.7	200	5	79	33.8
S6	Commercial district	1.77	202	5	83	34.1
S7	Commercial district	1.69	217	5	83	36.2
S8	Housing estate	2.87	332	10	79	31.8
S9	Housing estate	0.92	125	10	79	41.5
S10	Housing estate	0.64	120.5	10	79	22
S11	Green land	2.13	179	10	25	30.4
S12	Housing estate	1.93	199	10	79	36.5
S13	Housing estate	2.1	224	10	79	32.1
S14	Park	2.17	216	10	61	27.7
S15	Housing estate	3.8	321	15	79	21.1
S16	Park	3.65	381	15	61	20.7
S17	Park	8.18	560	15	61	9.7
S18	Housing estate	3.86	396	15	79	22
S19	Park	2.98	294	15	61	27.3
S20	Park	2.84	278	15	61	29.4
S21	Housing estate	1.58	188	15	79	41.4
Controlled Conduct No.		Roughness- <i>n</i> value	Shape of cross area	-	-	
C1~C49		0.015	Closed-Rectangular	-	-	

Data sources: Low-impact development manual [21] and CHYI-SHYANG CO., LTD. [20].

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