Analysis of Urban Flood-waterlogging and Design of Road Drainage System Based on LID

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Abstract: With the rapid development of the city, the issue of urban flood-waterlogging has become increasingly prominent. The construction of the “sponge” city in the flooding area and the design of low-impact development (LID) are the hot spots in the industry. This paper proposed the potential flooding area evaluation model (PFAEM) based on the grey relational analysis (GRA), combined with the grey correlation coefficient and the variation coefficient method. By using PFAEM, this paper scientifically selected key district “Shuangliu” from the seven administrative regions of Chengdu to construct, and this paper checked with the investigation results. This paper carried out a detailed LID drainage system optimization design for this area. The results of the research showed that the city road was the focus of the drainage construction of “sponge” city. In the design of city road, the building information model (BIM) technology was innovatively introduced to more intuitively demonstrate the internal design of the road drainage system. This paper discussed the effects of the traditional city road and the “sponge” city road from both quantitative and qualitative perspectives. The discussion showed that the application of “sponge” city roads significantly reduced the risk of city flooding, and BIM technology will have good application value and broad prospects in urban underground drainage.

KEYWORDS: Urban flood-waterlogging, Low-impact development, Grey relational analysis, Building information model design in road.

Introduction

In recent years, due to the imbalance of urban construction and drainage systems, and the drastic changes in the global climate, urban storms caused by heavy rain have become more frequent. (Liu, et al.,2015) In this context, "sponge " city which is characterized by natural accumulation, natural penetration, and natural purification came into being, and more and more attention and promotion of the engineering community. (Liu, et al.,2016) The Chinese government has also taken a series of measures to support and guide the “sponge” cities, reduce floods and water pollution in cities, and enable cities to behave like sponges in the face of drastic climate changes. Through the six measures of “seepage, stagnation, storage, net, use, and discharge”, 75% to 80% of the rainwater will be consumed and utilized on the spot. (Ji, et al.,2015)

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However, the construction of “sponge” city in the entire city is exactly unrealistic in China today. Urban planning layout, economic conditions, terrain and other factors have limited the scope of the construction of a sponge city. So the construction of the “sponge” city in the flooding area and the design of low-impact development (LID) are the hot spots in the industry. Feng et al. (2001) conducted in-depth analysis of the impact factors of urban flood disasters such as disaster-affected bodies, hazard factors, and pregnancies, and summarized the trend of urban flood disaster models. Zhang et al. (2016) studied the impact of urbanization on the flood process from the point of view of river basin production and convergence, and in-depth explored the main reasons for frequent floods in Chinese cities. Chen et al. (2016) explained the importance of sponge cities in the management of flooding and rain in urban areas through the roots of urban rainwater floods and urban floods. Du et al. (2016) introduced the importance of “sponge” city concept and its application in urban road engineering and proposed successful cases in the application of urban road engineering in China. Ghimire et al. (2013) thought that urban underground buildings were more complex and it was extremely challenging to construct an accurate and efficient urban flood model.

After compared the current research results, it could be found that most of the scholars' research on urban flood-waterlogging was mainly reflected in the causes of urban floods and the measures to reduce floods. However, few mathematical models were used to analyze and evaluated potential flood areas in cities. And in the “sponge” city design, some scholars had not yet introduced the building information model (BIM) technology. Based on this, this paper first used the grey relational analysis (GRA) to establish a regional assessment model of potential flood disasters, and taken the example of Chengdu, China as an example. The result showed the key district was the Shuangliu. And based on the analysis results, carried out a LID-based drainage system design for the road. BIM was used in the design process to achieve the standardization and information sharing of the 3D model of the “sponge” city. To verify the analysis results and correct the model and understand the people's ideas, this paper conducted an investigation on the development of the “sponge” city in Chengdu and the urban flood-waterlogging situation at first.

Methodology

Potential Flooding Area Evaluation Model(PFAEM). Chengdu is one of the first batch of sponge city pilots planned by the Chinese government. Due to the large size of Chengdu, it is difficult to directly build "sponge" city in the entire city. Therefore, this paper evaluated the district most likely to be flooding, to be able to more accurately conduct "sponge" city construction and promote "sponge" city. To achieve this, this paper first established potential flooding area evaluation model (PFAEM) by using the grey relational analysis (GRA), combined with the gray correlation coefficient and the coefficient of variation method, to scientifically select the key district for the construction of "sponge" city, and then further optimized the design of the district. Technical route is shown in Figure 1.

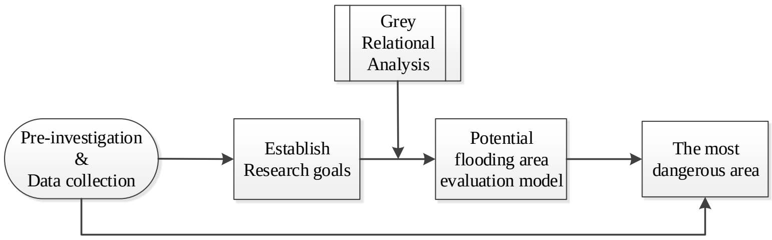

Figure 1-Steps for Potential Flooding Area Analysis

According to the system of urban natural disasters proposed by Yin et al. (2015), four indicators were selected in this paper: precipitation, water pollution, historical flood, and green area. This paper used these four indicators to establish the model. The steps for the establishment of the model are detailed in the appendix.

Results

Through the non-dimensional treatment of the original data of each district in Chengdu, and used the coefficient of variation method to obtain the weight of each indicator is shown in Table 1 below.

Table 1-The index weight of Potential flooding area evaluation model

Index	Precipitation	Water Pollution	Historical Floods	Green Area
Average	481.87	3.56	0.41	59.20
Standard deviation	397.82	1.55	0.15	223.96
Coefficient of variation	0.826	0.465	0.366	3.783
Weight(%)	15.3	8.04	6.76	69.9

Calculate the grey correlation coefficient of each index to get the gray correlation coefficient matrix. See the appendix for details. Then use equal weight method to get correlation degree matrix as follows.

$$B = \begin{bmatrix} 0.8271 & 0.4748 & 0.4985 & 0.6201 & 0.5693 & 0.4537 & 0.6741 \end{bmatrix}$$

According to the results of the correlation degree matrix obtained, the ranking of potential flood disaster hazards in various districts of Chengdu can be obtained as shown in Table 2. That is, the greater the degree of association, the higher the risk ranking of flood disasters.

Table 2-The rank of potential flooding area for districts in Chengdu

District	Shuangliu	Jinjiang	Chenghua	Jinniu	Wuhou	Pidu	Qingyang
Rank	1	6	5	3	4	7	2

From Table 2, it can be concluded that Chengdu's flood risk distribution heat map in Figure 2. The darker the color, the higher the flood risk level.

Figure 2-The distribution of flood disaster risk level

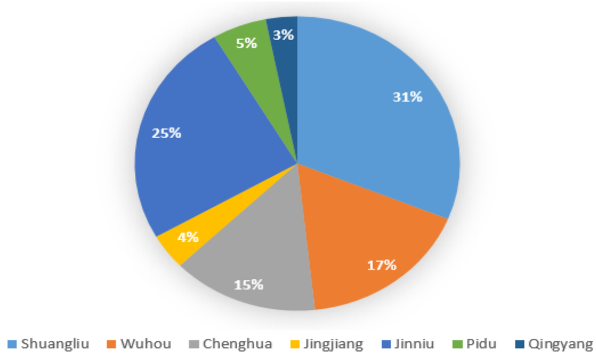

Figure 3-People's perception of flooding areas in Chengdu

From the data in Table 2, it is showed that the index vector of the Shuangliu has the greatest correlation with the ideal index vector, so the Shuangliu is the most likely district for potential flood disasters in Chengdu. In our investigation, the floods in various districts of Chengdu are also highlighted by the people, as shown in Figure 3.

Road underground drainage system design

LID-based Underground Drainage System. Based on available engineering measures that the 'Sponge City Construction Technical Guide' (Li et al., 2015) pointed out, this paper carried out a low-impact development (LID) system. This paper's LID system design flow chart as shown in Figure 4.

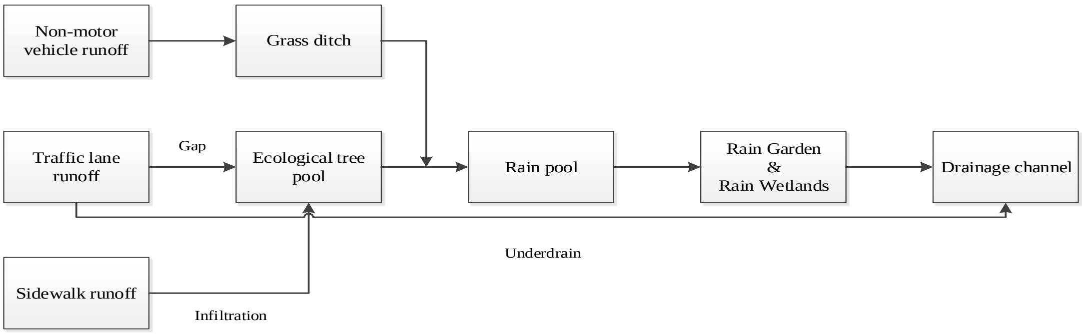

Figure 4-Flow chart of LID system design

According to the ‘Sponge City Construction Technical Guide’（Li et al., 2015）, the road design should adopt permeable pavement. Permeable pavement can be divided into pervious brick paving, pervious cement concrete paving and pervious asphalt concrete paving according to different surface materials. Pebbles and gravel paving in the embedded straw brick and garden paving are also permeation paving. The permeable paving is suitable for a wide area and is convenient for construction. It can supplement groundwater and has certain peak flow reduction and rainwater purification. In addition, the design of permeable pavement should follow the requirements of strength and stability of subgrade pavement. The plan and section of the permeable pavement are shown in the Figure 5.

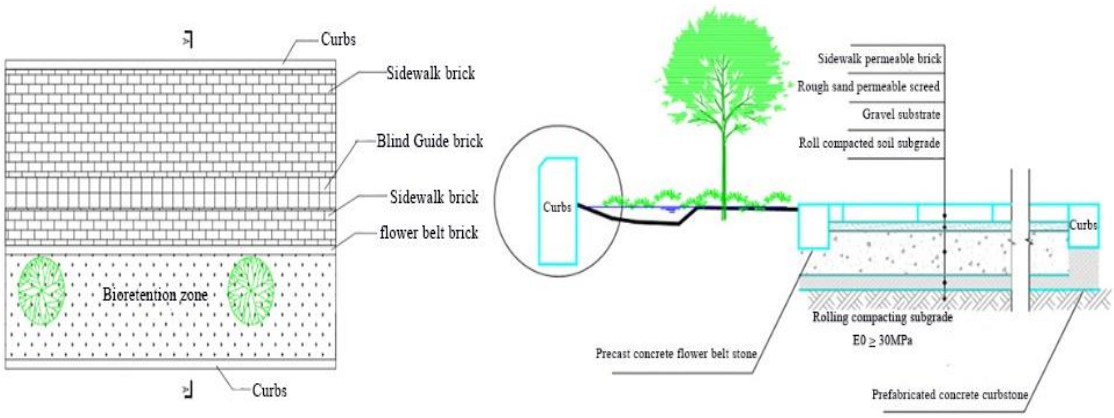

Figure 5-Permeable pavement (plan and section views)

The overall road layout design is shown in Figure 6.

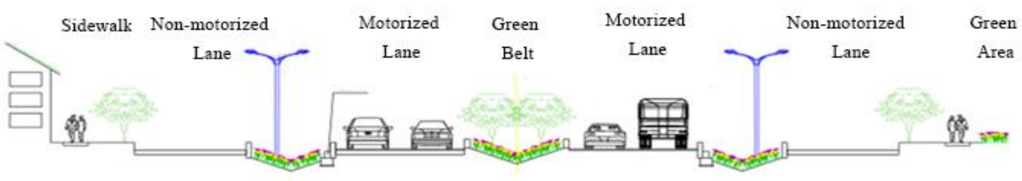

Figure 6- “Sponge” city four road cross-section arrangement type

"Sponge" City Road BIM Design. The building information model (BIM) originated in the United States (He et al., 2012), the General Services Administration (GSA) launched the BIM program in 2003 and has gradually developed guidelines and standards (Zhang et al., 2012) on BIM. China introduced BIM technology in 2003, but it is still in its infancy until today. BIM design principle is a drawing based on the plane. The internal structure model of the engineering project is created using software such as Revit. The design result can be visually and dynamically displayed so that both the investor and the constructor can intuitively understand the internal design scheme and can inspect. Meanwhile testable design constructability, to the effect of calibration.

The Establishment of BIM Model. The road Revit model can be directly designed in Revit software, or it can be imported and modeled based on the original AutoCAD design drawings. Either way, there are mainly two steps, namely determining the road section and drawing the road centerline.

Since "sponge" city road pavements are layered pavements, the profile of each road is the same. The establishment of the road 3D model is mainly based on the "sweeping" of the road section along the road centerline. Therefore, in Revit, it is necessary to first establish a section in which road pavements are layered and materials are allocated for each layer, and a family is created so that it can be swept along an axis. Then draw the road axis on the floor plan, and generate a 3D solid model by sweeping the road section. The final rendering is shown in Figure 7.

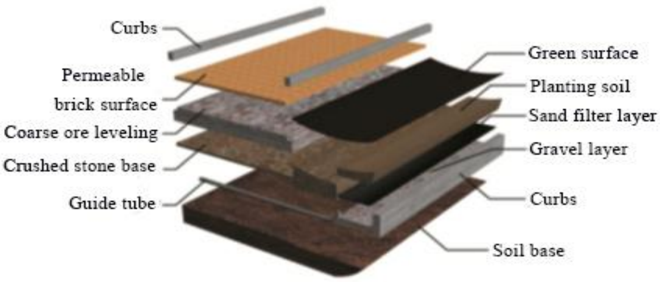

Figure 7-BIM Road model for "sponge" city

The Internal Structure of BIM Road Model. To facilitate the intuitive display of the internal structure of the sponge city, Revit was used to intuitively visualize the locations of the overflow, pipeline inspection wells, and planting soil on the sponge city road underground, as shown in Figure 8.

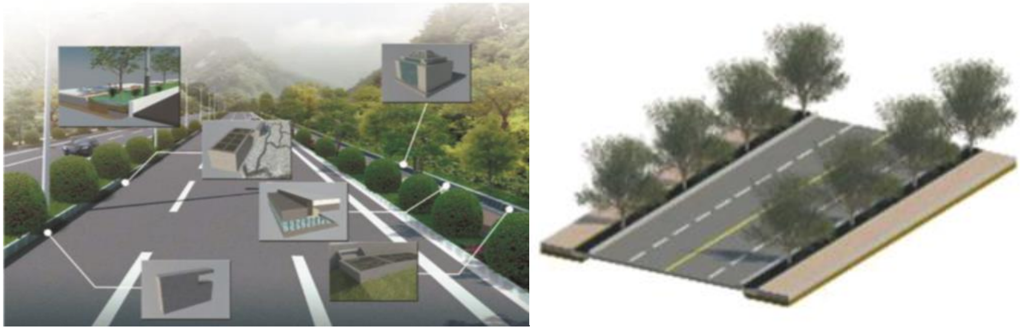

Figure 8-BIM Road internal structure for "sponge" city

Discussion

Spongy Urban Roads and Traditional Roads. Urban roads are an important part of urban space. The large amount of hardened ground in traditional urban roads weakens the penetration of rainwater. In rainy seasons, when rainfall is large, flood peaks are likely to form, leading to urban flood-waterlogging in some areas of the city. The urban heat island effect and greenhouse effect are exacerbated, and extreme weather conditions and extreme hydrological conditions are increasing. The use of LID technology facilities in sponge city roads can not only ensure the road capacity, but also prevent road drainage problems and prevent the impact of rain on the road stability. The 'Sponge City Construction Technical Guide'（Li et al., 2015）pointed out that the annual total runoff control rate, the rate of sewage recycling, the utilization rate of rainwater resources, and the leakage rate of water supply network can be used to assess the effectiveness of the "sponge" city. This paper compared traditional roads and "sponge" city roads from a quantitative point of view through numerical simulations. The results are shown in Figure 9.

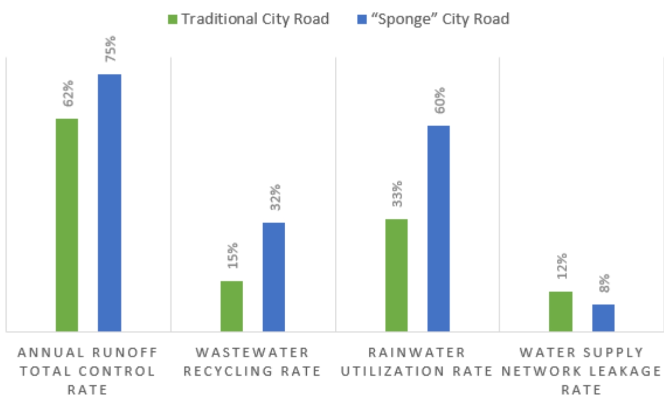

Figure 9-Comparison between "sponge" city road and traditional city road

From Figure 9, it is showed that use of "sponge" city roads designed in this paper can greatly reduce the risk of urban flood-waterlogging, while improving the utilization rate of rainwater resources and sewage regeneration and utilization. On the other hand, from a qualitative point of view, this paper summarized the differences between traditional urban roads and "sponge" city roads based on six aspects such as pavement paving. See Appendix for details.

From the above, it is showed that the "sponge" city road breaks through the traditional "row-based" urban stormwater management concept, and it has great promotion significance in reducing urban floods.

Comparison between BIM and AutoCAD Design. From the rendering, it can be intuitively found that using the BIM parameterization function makes the openness of the design results more effective, making the design more intuitive and intuitive. With the help of the characteristics of the BIM model information association, the adjustment, expression, and drawing of the program will become very simple. Due to reduced repetitive work, designers will have more time and energy to return to the solution of "sponge" city design problems.

Conclusions

For the urban flood problem, this paper combined quantitative and qualitative analysis to construct a district assessment model of potential urban flood-waterlogging. Based on the analysis results, the LID-based road drainage system design was targeted. Besides, this paper compared the traditional city road and the "sponge" city road and got the following conclusions.

1) The potential flooding area evaluation model (PFAEM) based on the grey relational analysis (GRA), combined with grey correlation coefficient and coefficient of variation method was proposed. From the four aspects of precipitation, water pollution, historical floods, and green areas, scientifically drawn potential flood disaster risk rankings for various districts of Chengdu. According to the potential flood disaster risk rankings, it was showed that the Shuangliu should be the key construction district of the "sponge" city, which was consistent with the investigation results;

2) A LID-based road drainage system was designed for the Shuangliu, and the BIM model was introduced into the design to more intuitively demonstrate the internal drainage structure design of the road underground engineering, providing more visual information and

management results;

3) By comparing the effects of “sponge” city roads and traditional roads in both quantitative and qualitative perspectives, as well as the effects of BIM and AutoCAD design programs, it was found that “sponge” city can reduce the probability of urban flood-waterlogging to a certain extent. The discussion also showed BIM will have wide application value and prospect in urban road underground drainage.

Credits

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Appendix

The steps for the establishment of the model:

Step1: Build an indicator matrix

Suppose we evaluate m samples, including n evaluation indicators, the reference number is $x_0 = \{x_0(k) \mid k = 1, 2, L, \ldots, n\}$.

The comparison series is $x_i = \{x_i(k) \mid k = 1, 2, L, \ldots, n\}$, and the corresponding index value is $r_{ij}(i = 1, 2, \ldots, m; j = 1, 2, \ldots, n)$; its index matrix is $R = (r_{ij})_{m \times n}$.

Step2: Determination of Indicator Weights

Due to the different dimensions of the indicators, it is not appropriate to directly compare the degree of difference. In order to solve the impact of different dimensions of the indicators, we need to use the index coefficient of variation to measure the degree of difference in the value of each indicator. The coefficient of variation for each indicator is as follows:

$$V_i = \frac{\sigma_i}{\bar{x}_i} (i = 1, 2, \ldots, n)$$

In the formula, V_i is the coefficient of variation of the i-th index, also known as the standard deviation coefficient; σ_i is the standard deviation of the i-th index; $\overline{x_i}$ is the average of the i-th index.

Thus, the weight of each indicator is:

$$W_i = \frac{V_i}{\sum_{i=1}^{n} V_i}$$

Step3: Calculate Gray Correlation Coefficient

$$\xi_i(k) = \frac{\min_s \min_t \left|x_0(t) - x_s(t)\right| + \rho \max_s \max_t \left|x_0(t) - x_s(t)\right|}{\left|x_0(t) - x_i(t)\right| + \rho \max_s \max_t \left|x_0(t) - x_s(t)\right|}$$

$\xi_i(k)$ is the correlation coefficient of the reference series in the k-th index, where $\rho \in [0, 1]$ is the resolution coefficient, and $\max_s \max_t \left|x_0(t) - x_s(t)\right|$, $\min_s \min_t \left|x_0(t) - x_s(t)\right|$ are respectively called the two-level maximum difference and the two-level minimum difference.

In general, the resolution ρ is proportional to the resolution. In this paper, the resolution coefficient takes the median value, which is 0.5.

Step4: Calculate grey weighted relevance

In this paper, linear weighted grey correlation is used. The formula is:

$$r_i = \sum_{k=1}^{n} w_i \xi_i(k)$$

In the formula, r_i is the gray weighted association degree of the i-th evaluation object to the ideal object.

Using the above formula to calculate the gray relational coefficient of each index, the gray incidence matrix can be obtained as follows.

$$\begin{array}{cc}
& \begin{array}{ccccccc} \text{Shuangliu} & \text{Jinjiang} & \text{Chenghua} & \text{Jinniu} & \text{Wuhou} & \text{Pidu} & \text{Qingyang} \end{array} \\
A = & \begin{bmatrix} 0.7163 & 0.4414 & 0.5514 & 0.3333 & 0.8028 & 1.0000 & 0.8687 \\ 1.0000 & 0.3929 & 0.6111 & 0.3826 & 0.3333 & 0.3793 & 0.3636 \\ 0.5923 & 0.5777 & 0.7615 & 0.9346 & 1.0000 & 0.9831 & 0.3343 \\ 1.0000 & 0.4029 & 0.3534 & 0.3443 & 0.3443 & 0.3340 & 0.3336 \end{bmatrix} \begin{array}{l} \text{Precipitation} \\ \text{Water Pollution} \\ \text{Historical Floods} \\ \text{Green Area} \end{array}
\end{array}$$

Table3: Comparison between “sponge” city road and traditional city road

Table 3-Comparison between “sponge” city road and traditional city road

Program	Traditional City Road	“Sponge” City Road
Design goal	Drain as soon as possible to reduce rainwater runoff	Rainwater runoff total, peak and pollution control from source, midway and end
Design idea	Drain the rainwater from the rainwater outlet	Some of them are infiltrated by LID facilities and some are discharged into rainwater pipes. The purified and treated rainwater is eventually discharged into the water body.
Differences	1. Hard water-proof pavement; 2. Non-porous curbs or rim stone; 3. Roadside rainwater drainage;	1. Permeable pavement; 2. Punch, gap curbs; 3. Drainage from undergrowth overflow;
Practical Effect	1. Less infiltration, low drainage efficiency; 2. Large network load and serious pollution; 3. Complex management and maintenance and unsightly design;	1. More infiltration, effective control of the amount of rain and flood; 2. Relieve network pressure and control surface pollution; 3. Simple maintenance, green and beautiful;

Table 4 LID Engineering measures that can be used in roads and surrounding areas

Table 4-LID Engineering measures that can be used in roads and surrounding areas

Part of Road	LID Measures
Pedestrian non-motorized lanes and motorized lanes	Permeable bricks, permeable concrete, etc.
Green separation belt	Bioretention zone (grass ditch), ecological tree pool, etc.
Motor and non-motor vehicle separation belt	Concave grassland, grass ditch, etc.