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Integrating Sponge City Requirements into the Management of Urban Development Land: An Improved Methodology for Sponge City Implementation

Dongdong Yang [1], Xin Zhao [2,*] and Bruce C. Anderson [1,3,*]

[1] School of Architecture, Tianjin University, Tianjin 300072, China; ydongdong0308@163.com
[2] School of Civil Engineering, Tianjin University, Tianjin 300350, China
[3] School of Engineering, Queen's University, Kingston, ON K7L 3N6, Canada
* Correspondence: jolson@tju.edu.cn (X.Z.); bruce.anderson@queensu.ca (B.C.A.); Tel.: +86-022-27404491 (X.Z.); +1-613-533-2122 (B.C.A.)

Abstract: Sponge city planning aims to manage urban development land to prevent flooding and to support the achievement of water resource protection objectives. In this study, from the perspective of rainfall management demand and ability, we present an improved planning method, including two calculation models, aimed at determining the VCRAR (volume capture ratio of annual rainfall) and then integrating VCRAR requirements into the management of urban development land more accurately and objectively, while simultaneously considering the rainfall condition and urban planning attributes to support the implementation of sponge city planning. Compared to the current method, the VCRAR calculation model greatly improves the accuracy of the VCRAR for various space scales, and the conversion model solves the fundamental problem that urban land indicators corresponding to the VCRAR are difficult to calculate objectively and accurately. Moreover, this methodology can achieve a reasonable tradeoff between the development of individual districts and the environmental protection of the whole urban watershed, which allows a poetic vision to be turned into executable planning and design. The results of the application of this methodology in a case study in Jizhou, China, show that the improved method can make land utilization, development period and natural conditions more integrated and scientifically involved in the indicator calculation. The results also quantitatively show that the capacity of volume capture inside the site for one district increases as its green space ratio increases, and it decreases with an increase in the transformation difficulty for stormwater management facilities, when restricted by the investment and available space.

Keywords: sponge city; stormwater management; volume capture ratio of annual rainfall; green space ratio; urban development land

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1. Introduction

Urbanization, resulting in the extensive development of impermeable surfaces and accelerated drainage, has been a principal driver of aquatic ecosystem degradation around the world in recent decades [1]. In China, the urban water environment has been severely damaged, and water issues have become acute. Between 2008 and 2010, at least 289 cities experienced varying degrees of flooding, accounting for 74.6 percent of the cities surveyed [2]. In 2013 alone, 234 cities were flooded due to extreme rainfall and runoff generation—exposing people to living quality threats and eroding billions of Chinese RMB from municipal assets [3]. Therefore, the problem of urban stormwater management in Chinese cities needs to be addressed urgently.

With this background, "sponge cities", where urban runoff can be captured, infiltrated, stored and purified for reuse, were proposed at the 2013 Central Working Conference on Urbanization. The concept of "sponge cities" was inspired by the literature on low impact development (LID) and best management practices (BMPs) in the USA, and water sensitive urban design from Australia, with the goals of reducing the burden of stormwater runoff on urban sewage systems and simulating the natural hydrological process through application of 'green' infrastructure, among others. Compared to typical LID measures that are small, local and piecemeal, "sponge cities" focus on an integrated urban water management approach to incorporate low impact development measures at the urban scale for the water environment, to protect the water ecology, water resources and water security [4,5]. As a new generation of urban stormwater management concept, which is greater in scope than comparable international initiatives [6], the reasonable indicators corresponding to the sponge city concept are the key to the implementation and development of sponge cities, which can transform the abstract concept of the sponge city into indicators that can be planned, constructed, and managed. It is beneficial for urban residents, relevant planners, government managers, construction units, etc., to fully understand the sponge [7,8]. Through integrating sponge city indicators into the planning and management of urban development land, the sponge city ecological infrastructure can be built from the spatial level of urban district, communities and sites systematically, which is very appropriate for Chinese cities' situation, with potential broader appeal and application.

In this regard, the Ministry of Housing and Urban-Rural Development of China put forward three control indicators to describe sponge cities in the Technical Guide for the Construction of Sponge Cities—Construction of Low-impact Development Rainwater System (Trial) (Technical Guide for short) [9], including the volume capture ratio of annual rainfall (VCRAR), the pollutant removal performance of annual runoff and the peak time delay of runoff. At around the same time, the Ministry of Water Resources of China proposed an indicator list for sponge cities relating to flood mitigation, recycling runoff, and recharging of groundwater, among other measures [10]. Although there are some differences between the indicators provided from the different government departments, it is generally accepted that the VCRAR is the primary control objective, since most of the other control indicators can be achieved by runoff capture and control [9,11]. The VCRAR refers to the proportion of runoff volume that can be controlled inside the site through natural or artificial measures like infiltration, storage, utilization or evapotranspiration, in comparison to the total annual rainfall. In China, the Technical Guide regards the VCRAR as a quantifiable target of sponge city construction and hopes to promote the implementation of the sponge city in urban land planning through VCRAR determination [9]. The indicators of urban storm water management vary from country to country, such as the United States. According to the technical guidance for implementing stormwater runoff requirements for Federal Projects under Section 438 of the Energy Independence and Security Act of 2007, the USEPA uses the rainfall event capture ratio as the target of urban LID construction and sets the target value [12]. Although the VCRAR values are not the same as the rainfall frequency percentiles [13–15]. The design storms in the United States are compliance metrics, not planning tools. Any given BMP might have a design that exceeds the compliance standard, depending on the site conditions and financial resources. In addition to the VCRAR, which guides sponge city planning, some evaluation index systems of sponge city construction projects are put forward with the consideration of wider social and environmental benefits [16], such as improved public health, enhanced natural cooling and improved biodiversity conservation, which can be used to measure the effectiveness of sponge city construction. The typical index system is divided into four aspects: aquatic ecology, water environment, water resources and water safety [8]. Although some systems include water ecosystem, socioeconomic system, and institutional and mechanism system [17], or contain rainwater collection and utilization, engineering indicator, flood storage capacity and ecological environment [18].

In order to set-up an overall target of urban sponge planning and construction in China, a method of acquiring an urban VCRAR according to the geographical zone is provided in the Technical Guide [9,19]. This method divides China's territory into five geographical regions from Zone I to V. Each zone has its own value interval of the VCRAR. For example, Zone I is located in drier northwest China and its interval of volume capture ratio is from 85 percent to 90 percent, while the interval of Zone V in the south of China (which experiences more precipitation) is from 65 percent to 85 percent. An urban VCRAR can be obtained through picking up a value in the value interval, but there are two major problems with this approach. One is that the recommended value interval for any particular zone is wide. The biggest difference between proposed values is 25 percentage points, which makes it difficult to determine a reasonable value of the volume capture ratio for one area or one city within a geographical zone. The other problem is that this method neglects the significant influence of the current urban development situation on the VCRAR, especially the ratio of green space and the volume-based runoff coefficient, for the implementation of the volume capture ratio method. As the construction and transformation of associated green infrastructure for stormwater management will be hindered by planning requirements for land modernization, pressure from land scarcity and land inflation [6]. Any green infrastructure, such as bio-retention, rain gardens or infiltration trenches, needs green space for rainfall infiltration and/or storage; this means the land utilization should be an important consideration when choosing the VCRAR value, aside from the rainfall condition itself. The current method takes into account only one of these two factors. This likely leads to a possibility that two cities with obviously different construction intensity in the same geographical zone may arrive at the same VCRAR value as their sponge city targets. The mismatch or contradiction between urban stormwater management objectives and urban development situation may cause problems such as land misuse and high investment. However, because this method to determine urban VCRAR is recommended by the Chinese national Technical Guide, which is akin to a Chinese national standard [16], there are few studies on how to determine the VCRAR by incorporating urban planning attributes. Under the overall target of urban VCRAR, some studies try to obtain the district VCRAR by proposed tables of VCRAR adjusted values, summarized by experts and relevant government authorities, which has positive significance for the implementation of sponge cities from the spatial level of urban, district and communities, systematically [20–22]. Moreover, in order to plan urban land use to achieve a VCRAR value that is in compliance, we further need to convert the VCRAR into urban land indicators, which should be consistent with the current land management indicators of urban planning and land management departments.

In view of these limitations, we improved and expanded the existing methods in China to incorporate planning approaches along with stormwater management in the following three ways. As an alternative to stormwater management, this method has the benefit of customization to suit the construction period, land use planning, construction density and things such as the recommended depth of submergible green space, to obtain a good site-specific set of results for an area, town or city, which is better for the overall goal of sponge city planning. We then applied this improved methodology in Jizhou's sponge city planning, in Hebei Province, China, to verify its scientific validity and comprehensiveness.

1. By simultaneously considering the rainfall condition and urban planning attributes, we established a reasonable urban VCRAR calculation model from an ability-oriented perspective, rather than the perspective of a rainfall management goal.
2. By clarifying the relationship between the VCRAR, volume-based runoff coefficient and the indicators for general land use planning, we established a more objective and improved conversion model between the VCRAR and land use planning indicators to implement the goal of sponge cities, by formula derivation, rather than by empirical evaluation.
3. By demarcating the computing units rationally, we provided a calculation model of the VCRAR for different scale spaces, which can help to implement the construction requirements of the sponge city from the urban scale to the communities' scale.

2. Methods

2.1. Set-Up of the Urban VCRAR Calculation Model

As one of the main means of stormwater management in sponge cities, especially for controlling runoff from moderate and light rains at the source, the ratio of green space (green space refers to land with vegetation as the main form within urban development land, including public parks, green buffer and attached green land) to urban development land has a direct and influential effect on the urban VCRAR, as well as being an important indicator for the planning of urban development lands and their capacity to function as runoff controls. Consequently, the core feature of the sponge city VCRAR calculation model is that it is derived from the ratio of green space to urban development land. In addition, the subjective experience of relevant experts and practitioners in the appropriate depth of submergible green space also needs to be introduced to support the determination of the VCRAR, especially at the urban scale.

The VCRAR calculation model was developed in five steps (Figure 1): (1) In this step, the recommended depth of submergible green space Δh was assessed through consultation with relevant experts and practitioners. (2) We ordered the urban development land into several types of land classifications according to land usage (Classification of Land usage types according to the Code for Classification of Urban and Planning Standards of Development Land (GB 50137-2011) [23], includes residential, administration and public services, commercial and business facilities, industrial, logistics and warehouse, road and transportation, municipal utilities, green space and square) and construction period. (In China, urban master plans are valid for 20 years, and some cities revise it more or less every 20 years. Therefore, the construction period can be divided according to the revision time of the urban master planning. This means that, in one construction period, the land construction indicators within the same land usage are similar, such as the ratio of green space, because the construction needs to follow the same version of the urban master plan.) We then evaluated the ratio of green space for each classification. In this model, the area with the same type of land use in the same construction period is the calculation unit. (3) With the area weighting method, we calculated the comprehensive volume-based runoff coefficients for different types of development land (every unit), through substitution of the ratio of green space. (4) The design rainfall depth for sponge cities planning was obtained through an area-weighted calculation of the design rainfall depth for every type of land classification in the urban development land. (5) A statistical computation was conducted to convert the design rainfall depth for sponge cities planning into the urban VCRAR. The individual steps are described in more detail in the following sections.

2.1.1. Assessing the Recommended Depth of Submergible Green Space

Through a semi-formal charrette type activity [24], the recommended value of the depth of submergible green space was assessed with the local relevant experts and practitioners, including soil geologists and hydrologists (who are familiar with local soil properties, groundwater level and rainfall conditions), urban planners and urban construction managers (who are experts on the specific urban situation and development, and understand the needs of urban land management and planning implementation), landscape designers and skilled gardeners (who are familiar with local plant growth and codes for the design of public parks) and some citizens (who are concerned about the function and appearance of the LID measures after they are built). The first step is to determine the upper limit of the depth. The maximum depression storage depth is determined mainly by soil geologists and hydrologists, according to soil permeability and the water table. In the second step, according to the growth characteristics of native moisture-tolerant plants and drought-tolerant plants, landscape designers and skilled gardeners need to identify the upper limit of water depth for the native plant growth, in consideration of the effect of the saturation on the plant growth environment, as the summer submergence can reduce growth and cause the death of some riparian grasses [25]. In the third step, the soil slope stability is an important factor to be considered, which has strong limitations on the depression storage depth of submergible green space, especially since green spaces in Chinese cities are generally small and compact. Urban planners and urban construction managers are familiar with this. Then, the depths determined from the above analyses need to be compared to select the minimum value, which can then be provided to the citizens for further discussion. Finally, the citizens invited to participate in the discussion can express their opinions on the depth of submergible green space from the two perspectives of comfort and aesthetics, providing the landscape renderings of submergible green space. If they agree on the depth, this becomes the recommended depth of submergible green space.

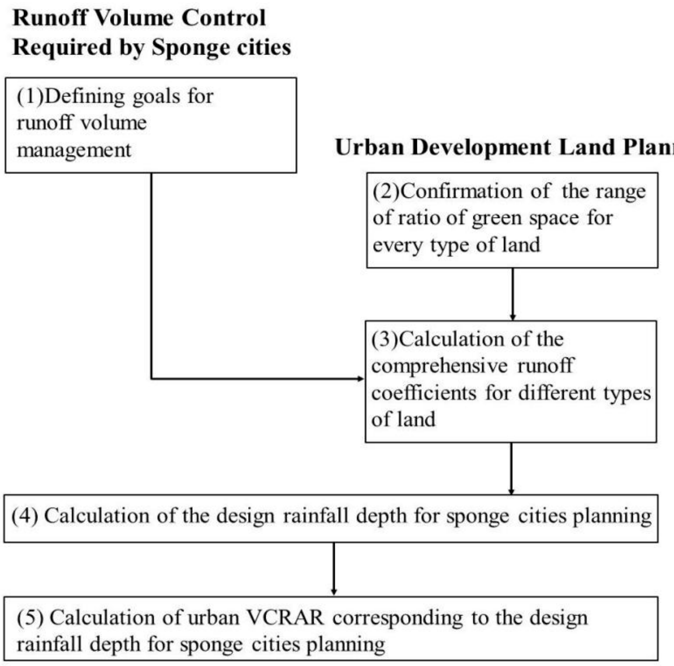

Figure 1. VCRAR calculation model and calculation process.

2.1.2. Definition of the Main Goal for Runoff Volume Management of Sponge Cities

As Aurbach (2010), Dhalla, Zimmer (2010) and MoHURO (2014) describe [9,26,27], the goal of urban stormwater management is to simulate the situation before the site is developed for human use (as a pre-development hydrograph). This indicates that too great a value of VCRAR does not necessarily signify a better and more appropriate goal of sponge cities, since the high design rainfall depth of the VCRAR corresponds to too much green space use and capital investment. This would make the strategy of sponge cities difficult to implement. Moreover, a too large VCRAR tends to promote the increase of urban rainwater utilization rate, but limits the groundwater recharge, especially in some water-deficient areas, which will be harmful to the water ecological environment. Alternatively, choosing a smaller VCRAR as the main goal may prevent the full performance and utilization of the green space stormwater management function. Therefore, selecting a suitable VCRAR not only needs to refer to the situation before the site is developed, but also should match the rainfall management ability of urban green space, highly influenced by the ratio of green space to urban development land and the submergible depth of green space (the amount of water that can be stored in the green space, as measured by the depth of submergence).

Given this, the main goal for rainfall management of sponge cities can be described by two aspects: (A) the difference in values of runoff depth between pre- and post- development under a certain rainfall condition, which can be calculated by Equation (1), from the perspective of rainfall management demand; and (B) the runoff depth that can be controlled by urban green space, which can be calculated by Equation (2), from the perspective of rainfall management ability.

$$\Delta h = H \times [\phi(\gamma) - \phi_0] \tag{1}$$

$$\Delta h = \gamma \times \Delta \bar{h} \times \alpha \tag{2}$$

where ϕ_0 refers to the volume-based runoff coefficient before urban development; $\phi(\gamma)$ refers to the comprehensive runoff coefficient after urban development, which has a functional relationship with the ratio of green space γ; H refers to the design rainfall depth; Δh refers to the runoff depth which should be controlled inside the site through the natural or artificially enhanced measures; and $\Delta\bar{h}$ refers to the recommended depth of submergible green space, which is assessed by the relevant experts and practitioners. α refers to the reduction coefficient of the effective volume of submergible green space, which is determined by its cross section. For example, for the bioretention cell, α is equal to 0.5. As the recommended depth of submergible green space refers to the depth of the deepest point of submergible green space and its cross section can be roughly equivalent to a triangle (Figure 2), its effective volume for runoff storage is 50% of the recommended depth multiplied by its footprint.

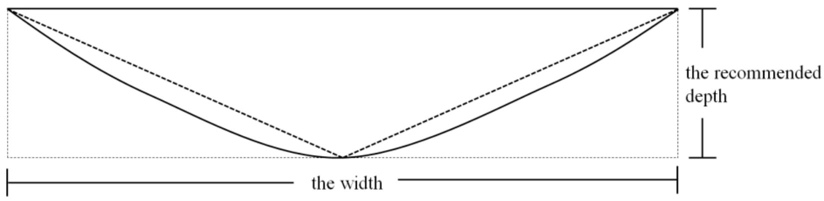

Figure 2. The typical cross section of the submergible green space.

2.1.3. Identifying the Ratio of Green Space

According to the Code for Classification of Urban and Planning Standards of Development Land (GB 50137-2011) [23] (including residential, administration and public services, commercial and business facilities, industrial, logistics and warehouse, road and transportation, municipal utilities, green space and square) and using a consideration of the stage of site development (for example, new district, built-up district and renewal district), the whole urban area can be expressed by several types of land. The range of ratio of green space for every type of land (γ_{min} to γ_{max}) is assessed in accordance with the criteria and requirements of land utilization planning in different stages of site development. For example, the ratio of green space for residential use in new districts is required to reach 30–40%, according to new criteria of land use planning, while in built-up districts it is usually 25–30%.

2.1.4. Calculation of the Comprehensive Volume-Based Runoff Coefficients for Different Types of Land

The comprehensive runoff coefficient for every type of land is calculated as per Equation (3):

$$\phi(\gamma) = \gamma\phi_0 + (1-\gamma)\phi_1 \tag{3}$$

where ϕ_1 refers to the runoff coefficient for impervious surfaces including concrete, asphalt road or roof, etc.

2.1.5. Calculation of the Design Rainfall Depth for Sponge Cities Planning

Because Equations (1) and (2) can be equated to each other, through incorporation of Equation (3) and rearrangement, the design rainfall depth for sponge cities planning can be calculated by Equation (4) as follows:

$$H = \frac{\Delta\bar{h} \times \gamma \times \alpha}{(\phi_1 - \phi_0)(1-\gamma)} \tag{4}$$

Because every type of land has a corresponding range of values of the ratio of green space (γ_{min} to γ_{max}), the value range of design rainfall depth (H_{min} to H_{max}) for each type of land can be calculated by substituting (γ_{min} and γ_{max}) in Equation (4).

Using an additive weighting approach, the value range of design rainfall depths for the whole city can be obtained (H_{min}^{city} to H_{max}^{city}) as follows:

$$H^{city} = \frac{\sum_1^m H_j^{type} A_j^{type}}{A^{city}} \tag{5}$$

where H^{city} refers to the design rainfall depth range of the whole city; H_j^{type} refers to the design rainfall depth of land type j; A_j^{type} refers to the area of land type j; A^{city} refers to the total area of the city; m refers to the total number of different land types.

Up to this point, the range of H for the city (minimum to maximum) can be calculated by Equation (5), using the various ranges calculated previously.

2.1.6. Calculation of Urban VCRAR for Sponge Cities Planning

There is a correspondence between the design rainfall depth and the *VCRAR*. According to the Technical Guide [9], their statistical significance is the proportion of total rainfall less than a certain amount in total rainfall. The rainfall (daily value) corresponding to the proportion (*VCRAR*) is the design rainfall depth (Figure 3). This correspondence can be described using the statistical approach as follows:

$$VCRAR^{city} = \frac{\sum_{j=1}^{k} H_j + (n-k)H^{city}}{\sum_{j=1}^{n} H_j} \times 100\% \tag{6}$$

where $VCRAR^{city}$ refers to the *VCRAR* of the whole city; n refers to the total number of rainfall events in the period of at least thirty years, according to the Technical Guide [9] (the rainfall events of less than 2 mm should be excluded); k refers to the total number of rainfall events less than H^{city}; H_j refers to the rainfall depth.

Finally, substituting (H_{min}^{city} and H_{max}^{city}) into Equation (6), the urban VCRAR (P_{min}^{city}~P_{max}^{city}) for sponge cities planning can be obtained by comprehensively considering the geographical zoning and the actual situation of urban development (as influenced by land use and construction period).

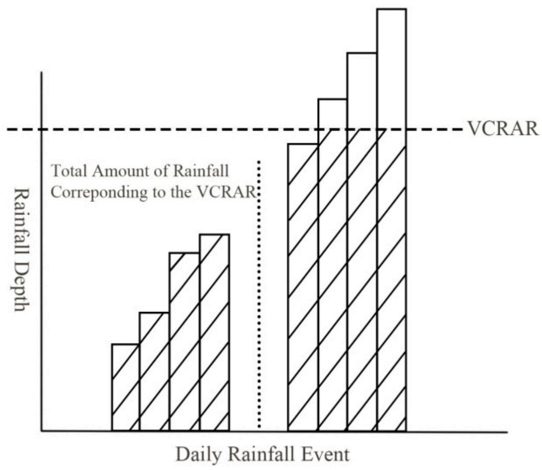

Figure 3. The statistical relationship between the VCRAR and the design rainfall depth (The x-axis is the daily rainfall events in the period of at least thirty years, in ascending order of daily rainfall amount).

2.2. Set-Up of the Conversion Model from VCRAR to Urban Land Indicators

Although the concept of the VCRAR is consistent with the strategy and requirements of sponge city planning and construction, this indicator is difficult to apply to directly guide urban planning and the administration of land utilization. Therefore, it is necessary to convert the VCRAR to more readily usable urban land indicators. This improved method makes it possible for the influencing factors related to urban development and natural conditions to participate in the indicator conversion calculation from VCRAR to urban land indicators, simultaneously and conveniently.

The precondition for the transformation of a stormwater management indicator like VCRAR into urban land indicators is the clarification of the relationship between the VCRAR, runoff coefficient and the indicators for general land use planning. As mentioned, the VCRAR is not only determined by design rainfall depth, but is also closely correlated with the runoff coefficient, which in turn strongly reflects the reality of land utilization and planning, to provide the important links between the VCRAR and urban land indicators. In view of the importance of the ratio of green space to total area γ, the ratio of permeable pavement to hard surface ω and the ratio of submergible green space to total green space θ, all of which correspond to the runoff coefficient by affecting the infiltration and storage ability of the urban underlying surface, the authors chose these three indicators to characterize urban land use planning for sponge cities.

With regard to the indicator conversion model from the VCRAR to urban land use indicators, a cyclic iterative computational method is proposed, and the types of land use mentioned in Section 2.1.2 are taken as the basic calculation elements. The process of iterative computation is shown in Figure 4. Firstly, a group of land indicator vectors (γ, θ, ω) is set for every type of land located in the urban area under investigation; secondly, the ratio of green space γ and the ratio of permeable pavement ω are used to calculate the comprehensive runoff coefficient for the whole city, using a weighting approach (Equation (7)), and then the produced runoff volume to be captured V_{runoff}^{Total} is obtained through substitution of the design rainfall depth, which corresponds to the VCRAR (Equation (8)). The third step, calculating the storage ability of each type of land, is assessed by the ratio of submergible green space, and then the total storage volume of the whole city V_S^{Total} is obtained (Equation (9)). Finally, based on the standard that the storage capability of submergible green space in the whole city V_S^{Total} should be slightly greater than the runoff produced volume V_{runoff}^{Total}, when the standard is not met, an adjustment can be made to the land indicator vectors (γ, θ, ω), according to the allowed value range required by the land utilization planning and the degree of difficulty of implementation, until this standard is satisfied. Accordingly, urban land indicators for every type of land are obtained under the requirement of the volume capture ratio of annual rainfall, achieving the conversion from the VCRAR to urban land indicators.

$$\phi = \frac{\sum_1^{\mathrm{m}} \left[\phi_G \times \gamma_j A_j + \phi_P \times \omega_j \left(1-\gamma_j\right) A_j + \phi_H \times \left(1-\omega_j\right)\left(1-\gamma_j\right) A_j\right]}{A^{city}} \quad (7)$$

where ϕ refers to the comprehensive runoff coefficient for the city; ϕ_G refers to the runoff coefficient for green space; ϕ_P refers to the runoff coefficient for permeable pavement; ϕ_H refers to the runoff coefficient for impervious surfaces including concrete, asphalt road or roof; ω_{j} refers to the ratio of permeable pavement of land type j; A_j refers to the area of land type j; A^{city} refers to the total area of the city; and m refers to the total number of different land types.

$$V_{runoff}^{Total} = \frac{1}{1000}(\phi - \phi_0)AH \quad (8)$$

where V_{runoff}^{Total} refers to the total runoff volume of the city needed to be stored. This is a target value. It refers to the increased runoff between pre- and post-development, under the design rainfall depth corresponding to a certain VCRAR, which needed to be stored by

LID measures; ϕ_0 refers to the runoff coefficient before urban development; and H refers to the design rainfall depth.

$$V_S^{Total} = \frac{1}{1000}\sum_{1}^{m}\theta_j\gamma_j A_j \Delta h \tag{9}$$

where V_S^{Total} refers to the storage capability of the submergible green space; and Δh refers to the storage depth of the submergible green space.

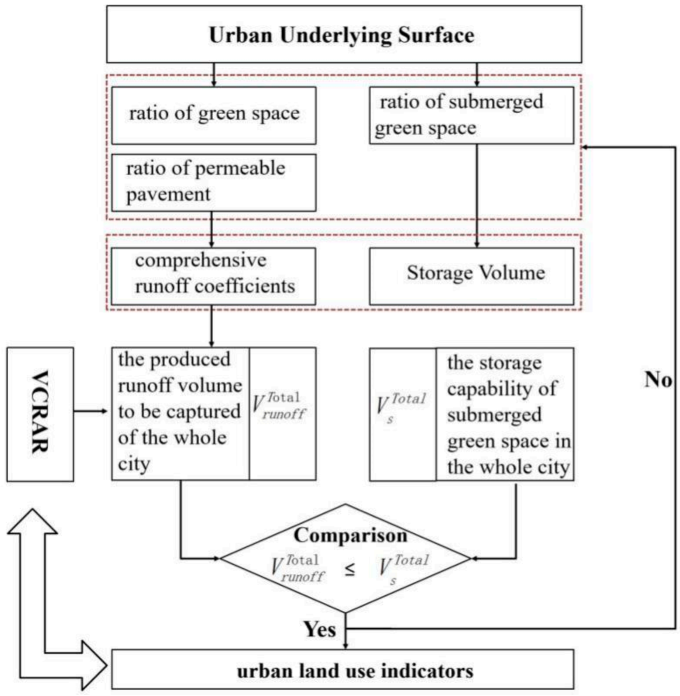

Figure 4. The indicator conversion model and calculation process from VCRAR to urban land indicators.

2.3. Case Study Area: Jizhou, Hebei Province, China

Located in the hinterland of the North China Plain, Jizhou is a city close to Hengshui Lake. There are four rivers flowing across this flat area into Hengshui Lake (Figure 5), so the groundwater table is high (less than 1 m below surface elevation). In addition, the vertical permeability coefficient of the first clay layer closest to the surface is 0.05 m/d with weak permeability.

Jizhou has a typical temperate and monsoonal climate with four clearly distinct seasons. Its average annual precipitation is 448 mm, with three important precipitation characteristics: (1) uneven distribution through the four seasons, with summer accounting for 67% of the total annual precipitation; (2) clear distinction between dry and wet seasons (average annual precipitation days is 67.8 days, while the days with rainfall intensity greater than 10 mm only accounts for 34.1%); and (3) precipitation variability from year to year, which may lead to drought and flood problems.

With the assumption of rainfall stationarity, using the daily rainfall event records from 1958 to 2010 provided by the Meteorological Bureau of Jizhou (2016), the precipitation data, excluding those events smaller than 2 mm, were sorted in ascending order. After ranking them in Percentile Function, the design rainfall depths corresponding to different VCRAR in Jizhou were calculated according to Equation 6 (Figure 6, Table 1).

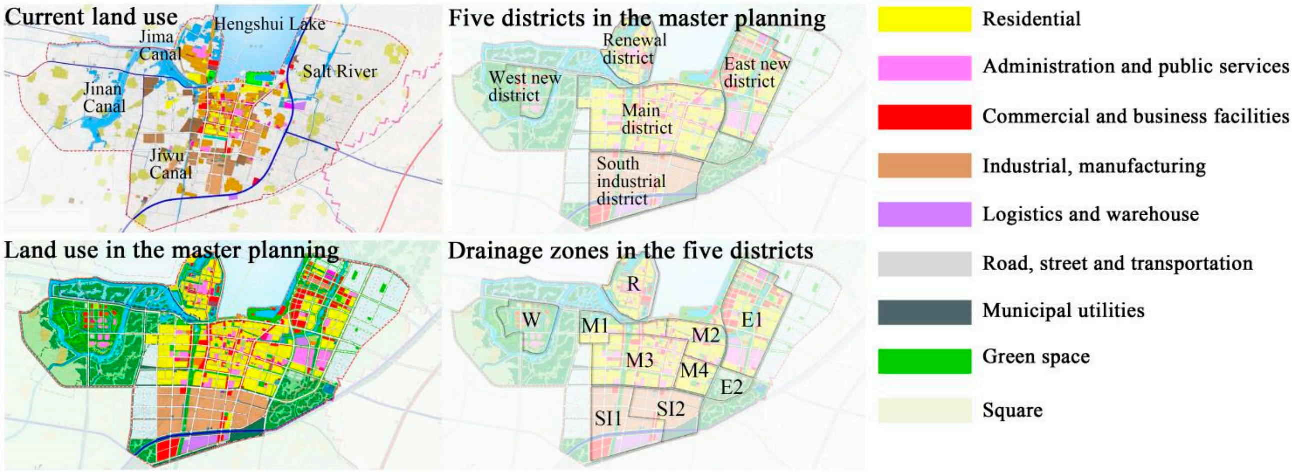

Figure 5. Land use and districts in current city and in the master planning of Jizhou 2015-2030.

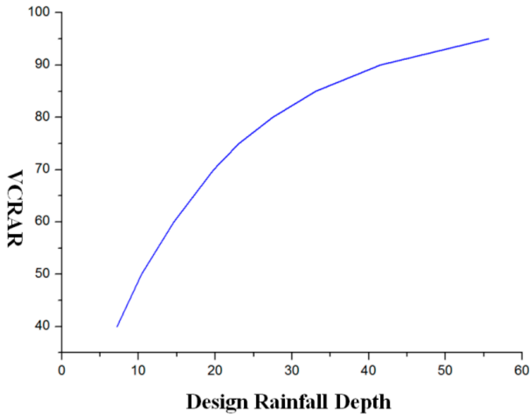

Figure 6. Corresponding relationship between VCRAR and Design Rainfall Depth in Jizhou.

Table 1. Correspondence between Volume Capture Ratio of Annual Rainfall and Design Rainfall Depth in Jizhou.

VCRAR	60%	70%	75%	80%	85%	90%
Design Rainfall Depth (mm)	14.6	19.8	23.1	27.5	33.1	41.5

After the year 2000, the city rapidly expanded southwards due to the restriction of the lake in the north. According to the updated urban master plan (2015–2030), the city will have a total planning development land area of 45.83 km^2, which is almost 2.5 times the current area, and will include the Renewal district, Main district, East new district, West new district and South industrial district (the area of each type of land use in each district is shown in Figure 7). With the sharp increase of urban impermeable surfaces, this will result in an increase in runoff volume in the Hengshui Lake watershed. Therefore, the government intends to reduce the negative effects on the water environment by changes to runoff generation and concentration through sponge city planning.

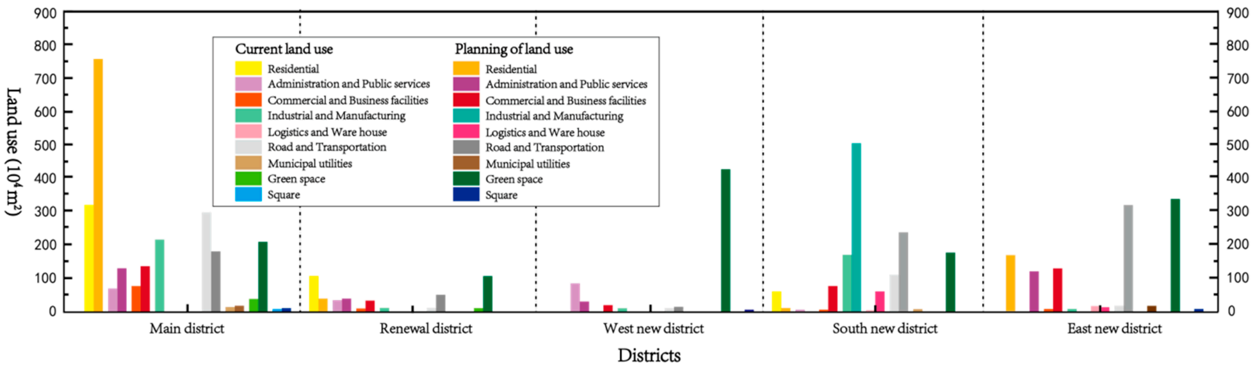

Figure 7. Land use and changes between current situation and the updated master plan.

Comparing the future planning land uses and the current land utilization, we found Jizhou will experience fast-paced residential and commercial development, particularly in the Main district and East new district, and the comprehensive runoff coefficient of the whole city would increase from 0.32 to 0.50, fostering a high demand for stormwater management. For each of the five districts, the comprehensive volume-based runoff coefficients will increase, among which the value of the urban central area (the Main district) is highest, and the value of the West new district and East new district are smaller as a result of the higher requirement for green space, which is attributed to the type of land and the construction period (mainly residential, administration and public services in these new districts). In addition, Jizhou's updated master plan proposes that all the industrial land will migrate from the Renewal district to the South industrial district, and there will be new green space and residential land in the Renewal district.

In view of MoHURO, 2011 and the Code of the Ratio of Green Space of Urban Development Lands for Jizhou (in different periods, the standards of green space ratio for every type of land changed according to the Code or the overall planning from the Ministry of Local Housing and Urban-Rural Development Bureau), and in combination with the current land utilization situation and the master planning of Jizhou, the value intervals of green space ratio for the nine types of development land in Jizhou are listed in Table 2.

Table 2. The range of ratio of green space for nine types of land use in Jizhou.

Types of Land	Stages of the Development		Residential (R)	Administration and Public Services (A)	Commercial Business Facilities (B)	Industrial Manufacturing (M)	Logistics and Warehouse (W)	Road and Transportation (S)	Municipal Utilities (U)	Green Space (G)	Square (G′)
Value intervals of green space ratio (% area)	Built-up district (Before 2000)	Min	25	12	12	12	12	5	15	65	20
		Max	30	25	25	15	15	15	20	90	30
	New district (After 2000)	Min	30	25	15	15	15	15	20	65	30
		Max	40	30	25	20	20	25	30	90	40

3. Results

3.1. Calculation of Urban VCRAR for Jizhou's Sponge City Planning

The recommended value of the depth of submergible green space for Jizhou was assessed with the local relevant experts and practitioners. During more than one hour, they avidly exchanged opinions to reach an agreement that 100 mm was an appropriate depth of submergible green space in Jizhou. This is mainly determined by the suitability of the plant growth. Influenced by the climate and soil conditions of Jizhou, the landscape architects considered that the main plants that can be planted in the submergible green space include *Juncus effusus* L., *Acorus calamus* L. and *Iris tectorum* Maxim., and the acceptable water depth for these plants is 100–200 cm. This depth is shallower than the water table (less than 1 m below surface elevation), meets the requirements of anti-sliding stability and the code for the design of public parks (GB51192-2016). Because of safety concerns, the citizens hope the depth of submergible green space can be shallow to avoid the elderly and children falling down. Therefore, a shallow depth of 100 cm was selected as the recommended depth of submergible green space in Jizhou.

As noted previously in Equation (3), γ for every type of land use is not a fixed value; rather it has a range of values which are strongly influenced by the construction or planning standard and development stage as shown in Table 2. For example, according to the remote sensing analysis, the green space ratios for the residential lands in the Main district are generally lower compared with other districts, and the minimum value of 25% corresponded closely to the construction standard of residential land in the 1990s. In contrast the green space ratios for some new residential space in the East new district reaches 40%, under the new higher standard from the master planning.

The value ranges of design rainfall depths for every type of land use in Jizhou were obtained by substituting the following parameters into Equation (4): here $\Delta\bar{h}$ equals 100 mm, α equals 0.5, ϕ_0 equals 0.32, the minimum and maximum values of γ are shown in Table 2, and ϕ_1 equals 0.5, and the results are shown in Table 3. Based on the corresponding relationship between the VCRAR and design rainfall depth in Jizhou (Figure 6), we also derived the value range of VCRAR for every type of land use (Table 4), which as the basic calculation unit can be used to obtain the VCRAR for any area or district in the city because any area or district in the city is composed of several types of land use. For example, the value range of design rainfall depth for every type of land use and their areas in the whole city are substituted in Equation (5), and the design rainfall depth for Jizhou's sponge city planning equals 31.7 mm–38.4 mm. According to Equation (6), the corresponding VCRAR for the whole city is 83.9–88.4%.

Table 3. The value range of design rainfall depth for every type of land use.

Types of Land	Stages of the Development		R	A	B	M	W	S	U	G	G′
Value range of design rainfall depth (mm)	Built-up district	Min	23.8	9.7	9.7	9.7	9.7	3.8	12.6	71.4	17.9
		Max	30.6	23.8	17.9	12.6	12.6	12.6	17.9	71.4	30.6
	New district	Min	30.6	23.8	12.6	12.6	12.6	12.6	17.9	71.4	30.6
		Max	47.6	30.6	17.9	17.9	17.9	23.8	30.6	71.4	47.6

Table 4. The value range of VCRAR for every type of land use.

Types of Land	Stages of the Development		R	A	B	M	W	S	U	G	G′
Value range of VCRAR (%)	Built-up district	Min	92.5	92.5	92.5	69.5	69.5	77.6	77.6	100	86.8
		Max	96.2	96.2	96.2	77.6	77.6	86.8	86.8	100	96.2
	New district	Min	96.2	96.2	92.5	77.6	77.6	86.8	86.8	100	96.2
		Max	99.8	98.7	96.2	86.8	86.8	96.2	96.2	100	99.8

3.2. Calculation of Land Use Indicators for Achieving the Goal of Jizhou's Sponge City Planning

The land use indicators for Jizhou sponge city planning are calculated at the drainage scale. Referring to the Special Planning of Drainage system in Jizhou, due to the encirclement by rivers, the Renewal district and the West new district are two independent drainage zones, and the Main district, South industrial district and East new district are divided into eight drainage zones (M1,M2,M3,M4;SI1,SI2, E1,E2). The scale and scope of each drainage zone are shown in Figure 5.

In accordance with the process of iterative computation shown in Figure 4, comprising Equations (7)–(9), the urban land indicators (represented by green space ratio, permeable pavement ratio and submergible green space ratio) for each type of land use in every drainage zone are calculated. Taking M2 in the Main district as an example, its land use indicators for the nine types of land use are shown in Figure 8 and Table 5. Based on this calculation, the general goal of Jizhou's sponge city planning is converted to the land use indicators, which can effectively guide the urban managers or designers to evaluate the scales of LID measures.

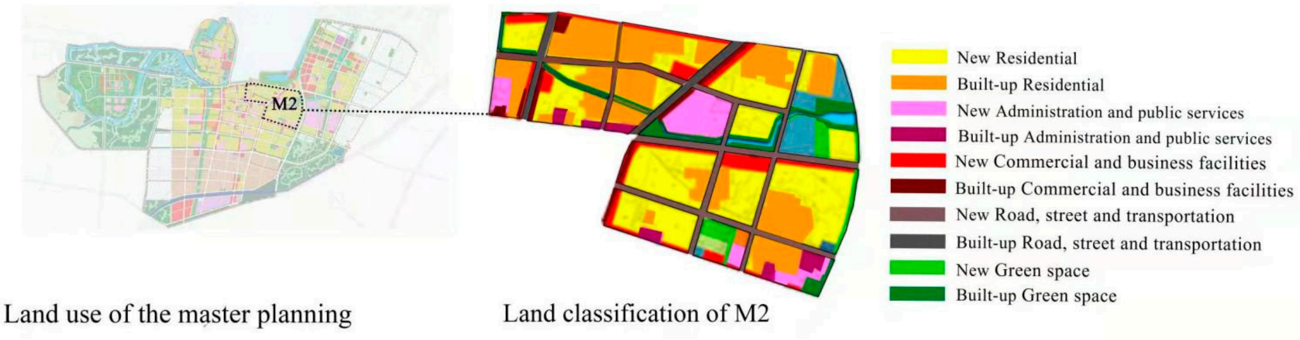

Figure 8. The map-based presentation of modeling results of land use indicators of M2.

Table 5. Land use indicators of M2.

Types of Land	Stages of the Development	R	A	B	S	G
value range of the ratio of permeable pavement (%)	Built-up district	30	20	20	0	55
	New district	50	40	40	5	65
value range of the ratio of green space (%)	Built-up district	30	25	25	15	70
	New district	40	30	25	25	85
value range of the ratio of submergible green space (%)	Built-up district	20	10	10	10	20
	New district	30	30	30	20	40

Based on the land use indicators, the computational accuracy of the comprehensive runoff coefficient will be improved through supplementing the parameter of ω in Equation (7). At a district scale, the VCRAR for every district can then be calculated and these are presented in Table 6. As expected, the West new district would have the highest target of runoff capture inside the site compared with the other districts because the ratio of the development land to total land is only 4.1%, with a higher quality of life attribute. For the South industrial district, where more than 50% of the area is used for manufacturing, warehouse and other industrial uses, with the lowest green space ratio, the VCRAR is also the lowest. For the three concentrated construction districts in Jizhou, their VCRAR ranking is East new district > Renewal district > Main district. These results conform to the principles and applicability for VCRAR determination that: (1) the more green space for runoff capture inside the site, the higher the VCRAR; (2) the more difficult it is to implement LID measures in one site (due to restrictions of investment and space), the lower is the VCRAR; and (3) the larger the portion of industrial land in one site, the lower the VCRAR, to reduce the proportion of runoff capture inside the site, encourage runoff into sewage-treatment plants through the drainage system for centralized treatment, and avoid contaminating the groundwater by heavy metal pollutants from the industrial district [28]. Moreover, this illustrates the importance of assessing the VCRAR for any individual district in the city in full correspondence to its land usage, and in comparison with the other districts in the city, as part of an integrated, holistic and realistic assessment.

Table 6. VCRAR for Every District in Jizhou.

District	Main District	Renewal District	South Industrial District	West New District	East New District
VCRAR (%)	80.6	86.3	61.5	96.5	87.5

4. Discussion

Establishing linkages between stormwater management and land utilization in the planning phase, to reduce runoff contributions to urban drainage systems and restrict negative impacts on hydrologic processes during urban rapid development, while still enabling urban growth and acknowledging the urban development stage, is a challenge for sponge city planning and implementation. The current methods follow an universal mechanistic approach of other methods, which are not customizable, and therefore the results may not be very suitable for a specific location. In this study, we showed how the two calculation models, the urban VCRAR calculation model and the conversion model from VCRAR to urban land indicators, allow integration of very localized information including types of land use, construction density, land development period and geographic factors, to evaluate the capacity of volume capture which the whole city and each district in the city can reach, and to then identify the land indicators which match the target VCRAR, which results in a good site-specific set of results for an area, town or city. Compared to the existing methods, this integrated methodology makes specific improvements in the following three areas, which is in our opinion better for the overall goal of sponge city planning:

1. Determining the VCRAR for the whole city based on evaluating the city's ability for runoff capture by green infrastructure. Currently, the geographical zone is the only basis for goal setting of sponge city planning, and it fails to consider the actual situation of urban development and construction level; this is intensively goal-oriented and somewhat unrealistic. To compensate for the problem of the current VCRAR determination method, the VCRAR calculation model in this research, which is based on fully understanding the relationship between the VCRAR, volume-based runoff coefficients, and the land utilization and development period, provides a way to determine reasonable VCRAR target values, by comprehensively considering the urban situation and geographical zoning, while also considering the potential limited ability of runoff capture inside the urban site. In other words, from an ability-oriented perspective, due to the differences in economic capacity and construction condition, it does not make sense to attempt to achieve the same VCRAR for two adjacent cities, located in the same geographical region. For example, Beijing and Langfang in China. The distance between the two cities is only 50.8 km. According to the current method recommended by the Technical Guide, they are located in the same geographical region, so the urban VCRAR of these two cities needs to be picked up in the same value interval. However, in fact, as Beijing is the capital of China, there is an obvious and great gap in the construction density between them; the urban VCRAR which can be obtained must be significantly different. The urban VCRAR calculation model proposed in this paper, from the perspective of capability, can solve this problem and reflect this difference of runoff control ability derived from site-specific urban construction and development information.
2. Proposing a more objective and improved method to construct the indicator system for a sponge city. The Technical Guide points out the indicator system for a sponge city is closely related to the underlying surface, land use type, the cost of sponge city construction and the natural environmental conditions. However, it is difficult to calculate them in practice. The most important reason is that all influencing factors have different dimensions, which makes it difficult for them to directly participate in the indicator calculation. The improved methodology here effectively solves this problem and the associated difficulties in deriving realistic planning information. As demonstrated, the influence of most of the factors representing urban development and construction (including land use type, construction density and land development period) on the sponge city indicators can be attributed to the ratio of green space. In addition, the recommended depth of submergible green space is determined by local experts and practitioners, based on their knowledge and experiences of soil properties, groundwater level, climatic conditions and rainfall conditions among others, which can reflect the influence of natural conditions on the control ability of

runoff capture inside the site. Therefore, the ratio of green space and the recommended depth of submergible green space are selected and introduced into the urban VCRAR calculation model and the conversion model to characterize the influence of many urban construction and natural factors on the indicator system. Comparing the improved and existing method, the calculation parameters of the improved method are the ratio of green space and the recommended depth of submergible green space, which can be determined on a solid basis (the former can be determined by the urban master planning, and the latter is recommended by local experts), while in the existing method, it is difficult to determine the design scheme of site LID measures according to the urban VCRAR, which has a huge scale difference, from hundreds of square kilometers to hundreds of square meters. Moreover, the design schemes vary from designer to designer. Through reasonable simplification and improvement, the problems existing in the current method for sponge city indicator system construction, which are subjective and difficult to rationally apply, can be solved.

3. Using areas with the same type of land use in the same construction period as the calculation unit to facilitate the management and implementation of sponge city planning. In China, the urban controlled and detailed planning for individual cities usually gives clear regulations on the ratio of green space for every type of land classification. Moreover, any district in the city, such as an administrative district, drainage district or function district, is typically composed of several types of land use from different construction periods. Therefore, through the proposed methodology, taking the area with the same type of land use in the same construction period as the calculation unit, the sponge indicators for any district in the city can be calculated regardless of scale. What needs to be done is to substitute the green space ratio and area of each type of land in the district into Equations (4)–(6), which overcomes the main problem of 'qualitative assessment' in the current method. For example, Wuhan [22] has proposed tables of VCRAR adjusted values, summarized by experts and relevant government authorities, which mechanically decompose the VCRAR from the urban scale to the district scale, through adding or subtracting an adjusted value to the VCRAR for the whole city [29]. It is evident that the existing method is strongly subjective and somewhat arbitrary. Nonetheless, in comparison with the existing methods, this proposed methodology makes full use of the common characteristics and the specific requirements on green space ratio of the same type of land use in the same construction period, and makes obtaining the VCRAR and the corresponding land indicators much simpler and more scientific. More importantly, from the perspective of planning implementation, the basic control unit of sponge city planning can be consistent with the control unit of the urban controlled detailed planning, thus facilitating the synchronous implementation of these two planning approaches and avoiding the contradiction that often appears in urban planning [30,31].

In the case of Jizhou, the application of this methodology is quite effective. The calculation process starts with the analysis of the ability for runoff capture inside the site for the individual types of land uses (Table 3). This makes it possible to obtain the indicators for three levels corresponding to the urban scale, district scale and drainage scale, and the urban land use indicators corresponding to the VCRAR in every district (Table 5), to guide the implementation of sponge construction and renewal projects. Currently, many cities' guidelines for sponge city construction try to give suggestions on land use indicators, especially on the ratio of submergible green space [32–34], but most of these are qualitative and too general to apply to all kinds of sites with different attributes (type, scale, or development period) because of a limited consideration of the implications of land use for the VCRAR. Though there is a small complication for the assignment of initial values for land indicator vectors to be computed iteratively, which need to reference the local general planning, controlled detailed planning and green space system special planning, and identify the local conditions, our method would certainly increase the validity of the land use indicator calculation and, importantly, foster consideration of a land's limited ability for runoff capture inside the site in the planning process.

One of the main challenges in applying this methodology is how to choose and determine the period at which the urban underlying surface can represent the land situation before urban development (the pre-development phase)—a topic also raised with the LID strategy and sponge city promotion. At a neighborhood scale, LID planners and designers usually intend to reach a higher goal of stormwater management by selecting the natural wild condition as the reference objective, especially for some demonstration projects. For example, the 10th@ Hoyt Apartments in Portland, Oregon, USA, designed by Koch Landscape Architecture in 2003, has the capacity to detain rainwater for approximately 30 h at a cost of USD 270,000 in an 8500 sq.ft. area [35]. However, sponge city planning mainly focuses on the large and medium scales. It is thus somewhat unrealistic to perform the sponge city planning referring to the natural wild condition, particularly for a large metropolis in China, which would mean unrealistically high investment and a large number of demolitions to provide room for storage or infiltration. It is known that Chinese cities' construction has gone through six stages [36,37], which provides some basis for choosing the reference point for pre-development runoff control targets. Usually, for large cities with a population over one million, their sponge city planning can choose the urban underlying surface around 1998 as the reference point, rather than selecting something from an earlier era, because after the rapid expansion (1998–2002), the characteristics of these cities are intensive but not old. The situation in the low-intensity period around 1998 is an achievable objective for these cities. For cities with a population less than 0.5 million, because of their slower development, their reference point for sponge city planning can be from an earlier era. In our case study, according to Jizhou's development characteristics and phase, we selected Jizhou's underlying surface in 1992 as the reference object. It is therefore necessary to undertake the research to understand the process of the urban development, and to evaluate (as accurately as possible) the comprehensive runoff coefficient of the city in different development periods, which will help in the selection of the current planning objectives.

Moreover, surface elevation has a profound influence on flow and time to runoff concentration. Further development of this methodology will use DEM to improve the model [38,39] and be linked to a GIS platform, allowing planners and managers to more easily access surface elevation and land utilization data, and to better understand the spatial distribution of planning indicators and information. Better spatially explicit visualizations on a GIS platform are known to facilitate collaboration between planners, managers and citizens.

5. Conclusions

Integrating sponge city requirements into the planning of urban development land not only provides a practical approach to better balance stormwater management indicators and the land utilization aspects of urban planning, but also can achieve a reasonable tradeoff between the development of individual districts and the environmental protection of the whole urban watershed. Compared to the generic indicators calculation method for sponge city planning currently in use, this methodology provides two important contributions to the implementation of sponge city planning: (1) proposing a more objective, improved and ability-oriented method of calculating the VCRAR and the corresponding land indicators for different scales of urban land, with simultaneous consideration of the natural condition, land utilization and development period, instead of the empirical estimates; and (2) in this methodology, with reference to the land utilization limitations and requirements of urban controlled detailed planning, the VCRAR and the corresponding land indicators of every type of land use classification are brought into focus, which is conducive to the integration and synchronous implementation of the existing urban control detailed planning and sponge city planning. Consequently, this integrated methodology is a much more appropriate approach to stormwater management, which better incorporates local information to solve the current difficulties of implementing sponge city planning. Fortunately, the results of the VCRAR and land use indicators for Jizhou have been used to guide Jizhou's sponge city construction, cited by the Jizhou sponge city special planning, which was approved by Jizhou's planning and management department from 2019, and the sponge city construction in Jizhou continues. We will continue to track the effectiveness of its construction.

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