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Exploration of waterlogging regulation path in the cities on the Loess Tableland in Northwest China based on the concept of Sponge City: a case study of Qingyang City in Gansu Province, a pilot city of National Sponge Cities

Qiushi Xu[a], Xiaohua Shi[b,*], Zai Liu[c]

[a]*School of Architecture, North China University of Water Resources and Electric Power, Zhengzhou 450046, China*
[b]*School of Architecture, Zhengzhou University, Zhengzhou 450006, China, email: 18544707@qq.com*
[c]*Beijing General Municipal Engineering Design and Research Institute Co., Ltd., Beijing 100082, China*

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ABSTRACT

In the face of global climate anomalies and frequent rainfall, China's large and medium-sized cities are extensively and frequently flooded, so urban waterlogging becomes increasingly severe. As an important means of management of rain and flood resources, Sponge City provides a new way to solve urban waterlogging. In this paper, taking the waterlogging regulation in the Old Urban Area of Qingyang as an example, with the construction of Sponge City as the concept, the current waterlogging was analyzed through the field investigation and simulation. According to the local characteristics of climate and rainfall, terrain, and topography, and soil and water body, systematic regional waterlogging regulation measures of "source reduction, process control, and terminal storage" were put forward address the actual situation of collapsible loess and soil and water conservation in the cities on the Loess Tableland, which provided experience and reference for similar water problems in other cities on the Loess Tableland in Northwest China.

Keywords: Sponge City; Waterlogging regulation; Low impact development

1. Introduction

Sponge City is a city that is like a sponge, which has good "elasticity" in adapting to environmental changes and dealing with natural disasters. When it rains, it absorbs water, stores water, seeps water, and purges water; when needed, it "releases" the stored water. It is a city construction concept with rainwater comprehensive control as the starting point, an important measure to coordinate water safety, water resources, water environment, water ecology, and other water problems, the main content of double urban repairs of "urban repair, ecological repair", which focuses on improving the natural and living environment as well as the quality of new urbanization.

Xixian New Area, Qingyang, Xining, and Guyuan are the only four pilot cities of National Sponge Cities in Northwest China. Among them, Qingyang is located in the tableland surface of "the first Loess Tableland of the world Loess Tableland" – Dongzhi Loess Tableland, the only Sponge City on the Loess Tableland in Northwest China. With an average sponge of 1,400 m, flat and broad Loess Tableland surface, surrounded by vertical and horizontal gullies, Qingyang is a typical gully landform on the Loess Plateau [1]. Due to the special geology of collapsible loess and the terrain of low water and high Loess Tableland (Fig. 1), it has no natural rainwater receiving bodies such as natural rivers, and waterlogging occurs in the Old Urban Area frequently. In this process, the rainwater lacks effective control, which leads to serious water and soil erosion, resulting in

* Corresponding author.

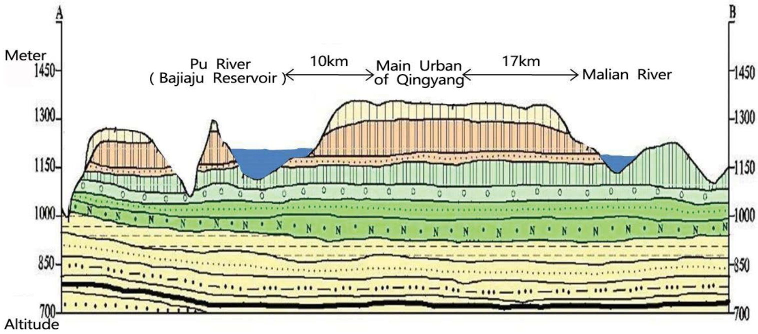

Fig. 1. Topographic and geomorphic profiles.

the advancement of gully heads and the collapse of Loess Tableland surfaces, thus, reinforcing the gullies, preserving the Loess Tableland, and protecting the city become imminent (Fig. 2).

In this paper, with the construction of Sponge City as the concept, according to the principle of adapting to local conditions, systematic regional waterlogging regulation measures for the waterlogging in the Old Urban Area of Qingyang were put forward to realize water safety and water ecology in Sponge City and discuss the solutions, technical methods, and control points for similar water problems in the cities on the Loess Tableland, which provided experience and reference for similar water problems in other sponge cities across China [2].

2. General construction situation of Sponge City-Qingyang

Located in the eastern part of Gansu Province, the area of Central Urban Area of Qingyang is 210 km^2. Of which, the area of construction land is 70.43 km^2, including the Old Urban Area, New Urban Area, Xifeng Industrial Park, and Xifeng Industrial Concentration District. The North Urban Area and South Urban Area link up into a single stretch, and the parks are relatively independent (Fig. 3).

Qingyang belongs to continental climate with annual average temperature of –8.4°C to 23°C, annual average rainfall of 539–828 mm, and annual average evaporation of 506 mm [3]; a typical loess development area with self-weight collapsibility grade III (serious).

Qingyang has three artificial lakes – North Lake, South Lake, and East Lake, covering an area of 1,400 mu. The rainwater outside it is discharged into Pu River and Malian River in the lower Loess Tableland, causing up to 700 t/km^2 a of water and soil erosion amount in the urban area, namely serious water and soil erosion.

Qingyang, a Sponge City, establishes the total annual runoff control rate of 90% as the construction goal, and achieves “no waterlogging in case of heavy rain, no accumulated water in case of small rain, no water, and soil erosion” by taking technical measures of “focusing on regulating storage, supplemented by infiltration, and strengthening reuse” [4]. At present, it has launched 21 model projects for the construction of Sponge City, and invested 354 million yuan, involving the sponge transformation of road, district, green space, and square; it has carried out the inspection of pipe network in the Old Urban Area and the approval of waterlogging points; it has set up Sponge City data monitoring equipment, and built sponge pipe control platform and intelligent sponge system.

3. Analysis of the waterlogging in the Old Urban Area of Qingyang

3.1. Distribution of current waterlogging

3.1.1. Field survey

According to the meteorological monitoring data and rainstorm statistics through the years, the waterlogging points were located in the surrounding areas of Xiaoshizi and Beijing Avenue in the Old Urban Area. In a heavy rain on August 20, 2010, the deepest accumulated water on the Beijing Avenue was more than 1 m. In a heavy rain on

Fig. 2. Diagram of the relationship between the Urban Area and the gullies.

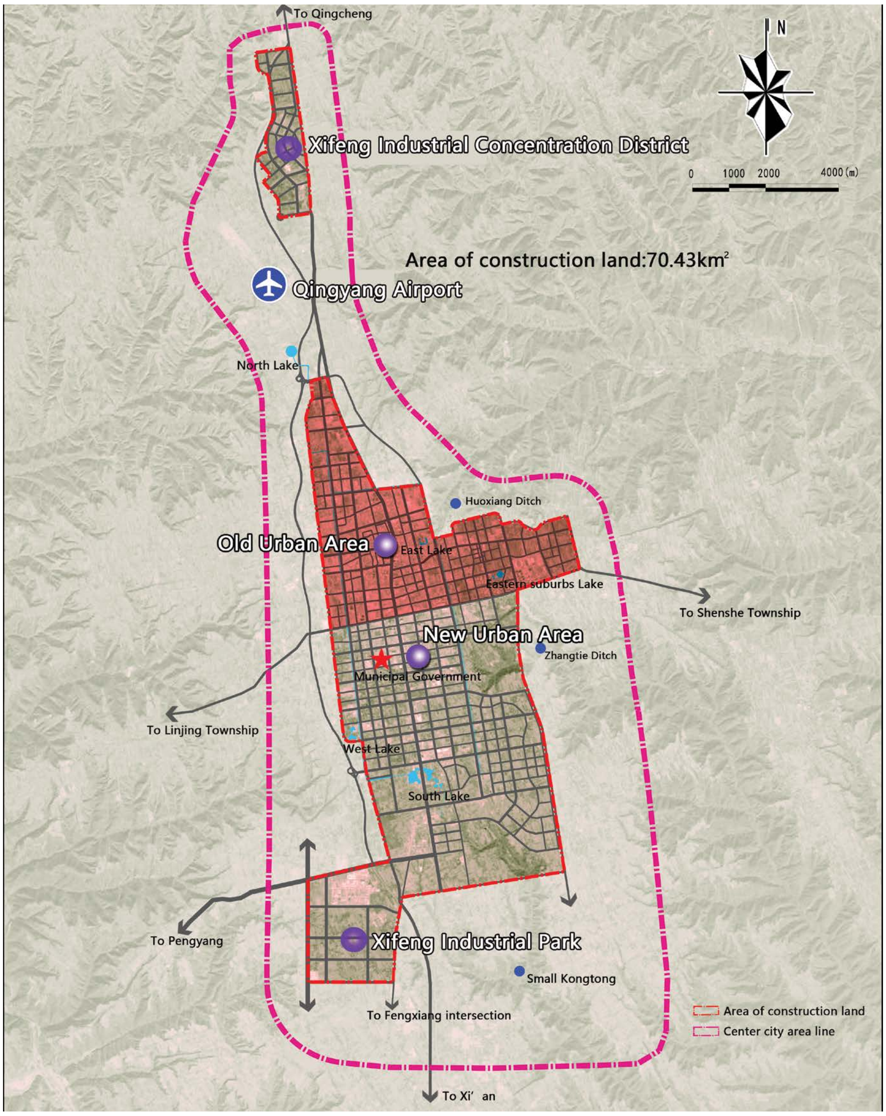

Fig. 3. Diagram of the location and scope of each area in the Urban Area.

August 3, 2015, the maximum rainfall within one hour reached 45.7 mm, rainwater pouring in the Xiaoshizi business street.

3.1.2. Model evaluation

Through the infoworks model combining with the current network, terrain conditions, and rainfall standards, an evaluation of the waterlogging in the Old Urban Area was carried out. The evaluation standard was 30 y event design rainfall, and the total rainfall was 71.30 mm.

When the depth of accumulated water $0.18 < h \leq 0.3$, and the time of water accumulation $t < 30$ min, the risk grade of waterlogging was low risk area [5], requiring no special treatment as the water accumulation was not a water accumulation disaster. When the depth of accumulated water $h > 0.3$ m, and the time of water accumulation $t > 30$ min, the risk grade of waterlogging was high risk area, requiring drainage in time as the water accumulation was a water accumulation disaster.

According to the evaluation of the waterlogging in the Old Urban Area, there were 15 waterlogging points, which mainly located in Xiaoshizi, East Lake, Baota Road, and Lanzhou Road.

3.1.3. Distribution of current waterlogging

According to the field survey and model evaluation, there were 17 waterlogging points in the Old Urban Area, and the area of waterlogging was 24.26 ha (Fig. 4, Table 1).

3.2. Analysis of the causes of waterlogging

3.2.1. Concentrated distribution of heavy rainfall led to the frequent waterlogging

The rainfall in Qingyang was concentrated and had obvious seasonal change, with 80% rainfall in July–September. The short duration was mostly within 3 h (Fig. 5), and the

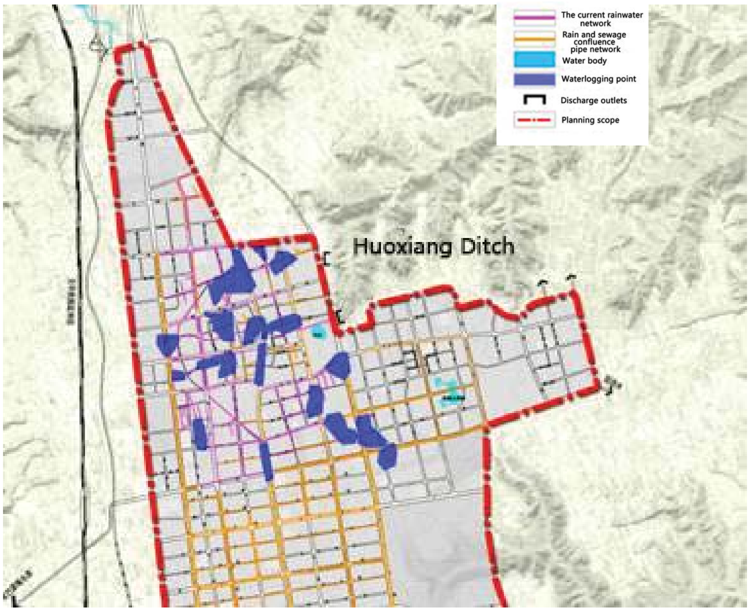

Fig. 4. Diagram of evaluation of the range of waterlogging points in the Old Urban Area.

long duration was 24 h (Fig. 6). The rainfall belonged to the single peak back rainfall type, characterized by fewer rainy days, large magnitude, concentrated rainfall, and more showers. 76% of heavy rain occurred at this time, which can easily cause large rain and flood.

3.2.2. High density construction of the Old Urban Area and rich micro-topography led to the difficult drainage of rainwater and serious water accumulation

The underlying surface of the Old Urban Area was divided into seven types: roofing, paving, pavement, green space, bare soil, water body, and agricultural and forest lands. The current agricultural and forest lands which accounted for 61% of the total land had good natural state before development [6]. Through calculation, the comprehensive rainfall runoff coefficient of the Central Urban Area was 0.36, which was 0.72 in the Old Urban Area and 0.58 in the New Urban Area. The Old Urban Area had obviously higher hardening rate than the New Urban Area, high construction density, and brought about great change to the natural conditions (Fig. 7).

Through the Arcgis analysis, the current topography was slow overall, and the slope in the Old Urban Area was mostly 0%–8% [7,8]. However, the micro-topography was rich, and there were many regional low-lying points, so the difficulty of drainage increased (Fig. 8).

3.2.3. Serious rainwater retention due to backward pipe network construction and disorderly overflows accelerated the water and soil erosion

The drainage system of the Old Urban Area was a confluence system, and the drainage capacity of more than half of the pipe network was less than 1 y event. Most of the flood drainage facilities in the roadways in the Old Urban Area had insufficient drainage capacity or there were no flood drainage facilities in the Old Urban Area [9]. During heavy rain, the rainwater flowed along the surface to the streets and roadways, and the residents living in the low-lying areas were still affected by flooding. At present, there were two discharge outlets in the lower Loess Tableland,

Table 1
Area of waterlogging points and depth of water immersion in the Old Urban Area

Number of waterlogging points	Area of waterlogging (ha)	Maximum depth of water immersion (m)
Waterlogging point 1	0.62	0.3~0.7
Waterlogging point 2	1.22	0.3~1.2
Waterlogging point 3	0.91	0.3~0.7
Waterlogging point 4	1.21	0.3~0.8
Waterlogging point 5	1.12	0.2~0.8
Waterlogging point 6	2.55	0.4~1.2
Waterlogging point 7	1.25	0.3~1.1
Waterlogging point 8	0.91	0.2~0.4
Waterlogging point 9	1.69	0.3~0.7
Waterlogging point 10	3.01	0.5~1.4
Waterlogging point 11	2.48	0.5~1.1
Waterlogging point 12	1.23	0.2~0.5
Waterlogging point 13	0.89	0.2~0.4
Waterlogging point 14	1.24	0.3~1.2
Waterlogging point 15	0.29	0.2~0.5
Waterlogging point 16	0.61	0.2~0.6
Waterlogging point 17	3.03	0.3~0.7
Total area	24.26	

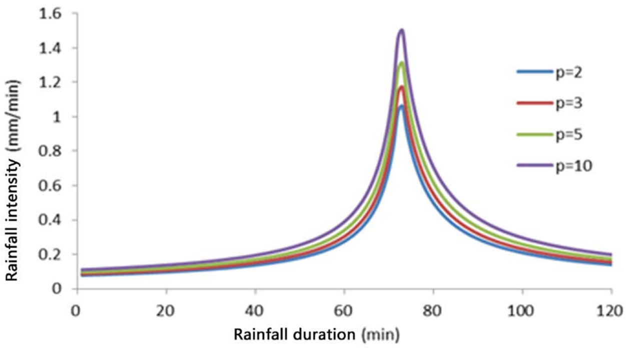

Fig. 5. Short duration (180 min) rainfall type.

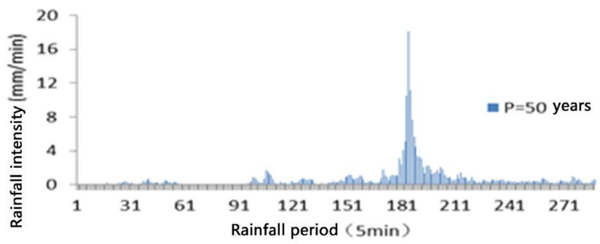

Fig. 6. Long duration (1,440 min) rainfall type.

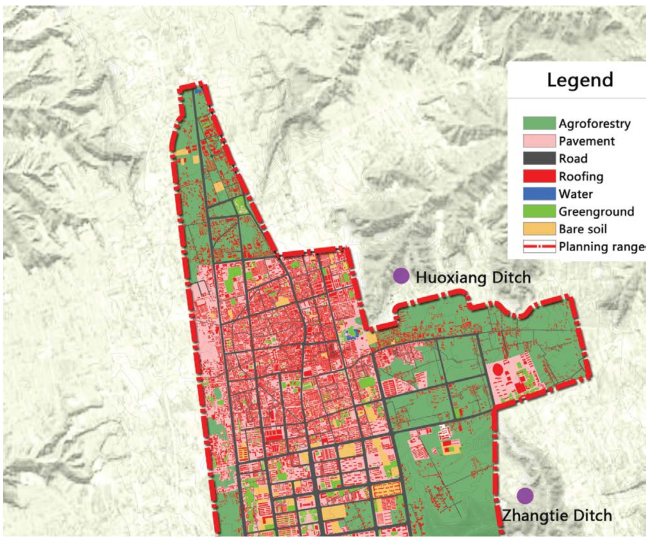

Fig. 7. Map of the underlying surface of the Old Urban Area.

but they had insufficient drainage capacity, resulting in water and soil erosion, collapse of gullies, advancement of gully heads and collapse of Loess Tableland surfaces, etc.

4. Regional waterlogging regulation strategy based on the concept of Sponge City

The traditional waterlogging regulation is to improve the urban drainage system, enhance the urban drainage capacity, and emphasize the rapid discharge, but the quantity of the project is large and the efficiency is slow [10].

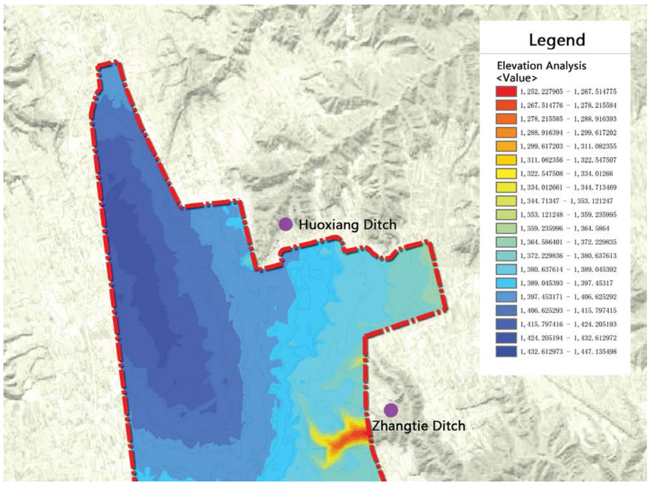

Fig. 8. Map of the elevation of the Old Urban Area.

Compared with the traditional waterlogging regulation method, the Sponge City focuses on "slow discharge, priority green facilities first, gray facilities support" [11]. Its core is to achieve source consumption and process control by setting up low impact development facilities and regional storage facilities, thus can effectively organize rainwater runoff, effectively alleviate the pressure of the drainage pipe network in the Old Urban Area and reduce the scouring to the Loess Tableland by the rainwater in case of heavy rainfall, so as to eliminate the waterlogging in the Old Urban Area by combining the detention and storage and changing the space with time.

The hydrogeology of Qingyang is characterized by concentrated rainfall, greater evaporation than rainfall, loss of natural water system and highly collapsible loessial soil layer. In addition, the Old Urban Area has the characteristics of high construction density, low infrastructure level, and extensive rainwater organization, etc [12–14]. Therefore, the waterlogging regulation of Qingyang should highlight the regional characteristics and adapt to the local conditions.

4.1. Low impact development rainwater facilities should highlight the suitability to the collapsible loess areas

When the collapsible loess was not soaked in water, generally, its strength was high and its compressibility was small. When the collapsible loess was soaked in water under a certain pressure, its structure will be destroyed rapidly, resulting in the large additional settlement, thus its strength will decrease rapidly, which will cause geological disasters such as subsidence of foundation, ground fissures, and landslides [15]. Considering the loess characteristics of the collapsible loess areas, pay attention to be "suitable for infiltration" or "careful in infiltration" when using the low impact development facilities and avoid the low impact development facilities with deep and large infiltration; pay attention to take reinforcement and anti-seepage measures such as laying geotextiles and lime soil when using the low impact development facilities with shallow and small infiltration; take anti-seepage measures for the roadbeds of carriageways; ensure the safety of surrounding buildings when selecting the position and taking anti-seepage measures for the rainwater storage facilities such as transport grass gullies and rainwater ponds.

4.2. Rain and flood control process should highlight the adaptability to the water and soil erosion areas

The Urban Area of the cities on the Loess Tableland and the gullies were interdependent. The water and soil erosion led to a sharp decrease in the Loess Tableland surfaces and even the safety of the cities, and the gully heads of Huoxiang Gully in the Old Urban Area of Qingyang had gone deep into the Urban Area. Considering the "Loess Tableland reinforcing and city protecting" demand of the water and soil erosion areas, strengthen the rain and flood process control, and arrange the regional storage facilities combining with rainwater partitions, topographic verticality, pipe network conditions, and runoff control targets to achieve the nearest centralized storage of rainwater [16]; plan the flood discharge channels combining with the main roads and greenbelts in the city, and orderly organize the rainwater into the regional rainwater storage facilities and artificial lakes, reduce the terminal rainwater storage capacity, and avoid the direct scouring to the gullies by the accumulated water in the Old Urban Area and rainwater runoff.

5. Waterlogging regulation scheme in the Old Urban Area of Qingyang

5.1. Source reduction – decomposition of low impact development indexes

The key to the source reduction was the form and scale of the low impact development facilities of the blocks, which were controlled mainly by the low impact development indexes. According to the local planning and control requirements, the low impact development indexes were divided into control indexes and suggested indexes (Table 2). In the process of decomposition of the low impact development indexes, it was required to establish storm water management model (SWMM)models and set up various low impact development facilities and input parameters to verify whether the runoff control rate and pollutant reduction rate reached the standard.

The steps of decomposition of the sponge indexes of the blocks were as follows:

- The goal of total annual runoff control rate of each drainage area was implemented according to the master plan.
- The control indexes of the sponge cities in each block were preliminarily proposed according to the underlying surface of the blocks combining with the control standard of the sponge indexes of the "List of control indexes of the sponge cities in all kinds of construction lands";
- The quantitative relation between the total annual runoff control rate of each block after area weighting and averaging and the total annual runoff control rate in the drainage partitions was calculated. If they were not less than this value, the assignment of the sponge indexes of each block was reasonable; if they were less than this value, the sponge indexes of each block should be debugged again until they were not less than this value (Fig. 9).
- The low impact development indexes of the sponge cities in each block were determined to obtain the corresponding design rainfall, and the storage capacity of each block was calculated.

5.2. Process control-construction of super-standard rainwater storage system

On the basis of low impact development facilities, the current waterlogging points were reevaluated using

Table 2
List of control indexes of the sponge cities in all kinds of construction lands

Construction item	Construction land type		Suggested low impact development minimum control indexes				
			Control indexes		Suggested indexes		
			Total annual runoff control rate	TSS removal rate	Green roof rate	Sunken green space rate	Permeable paving rate
Building and site	R	New construction	90%	50%	10%	75%	60%
		Reconstruction	88%	45%	5%	70%	50%
	B, A	New construction	88%	50%	10%	75%	60%
		Reconstruction	86%	45%	5%	70%	50%
	M, W	New construction	87%	60%	5%	60%	65%
		Reconstruction	85%	55%	5%	55%	60%
Municipal road	S	New construction	60%	50%	–	85%	93%
		Reconstruction	55%	45%	–	80%	90%
Park green space and square	G1, G3	New construction	93%	60%	–	80%	70%
		Reconstruction	90%	55%	–	75%	65%
Water body	E1	–	–	50%	–	–	–

Note: (1) Public buildings were larger than private property; (2) the land with high greening rate had good sponge construction condition and high total annual runoff control rate; (3) the planning area with collapsible loess took semi-permeable anti-seepage measures, and prudently took permeable paving modification measures; (4) reconstruction was less than new construction.

the infoworks waterlogging model. The results showed that the waterlogging points were reduced to 8, and the area of waterlogging was reduced to 16.98, and the depth of accumulated water was reduced.

The super-standard rainwater confluence area and path were planned combining with the terrain and topography, the regional storage facilities were reasonably planned for storage using roads and street greening as discharge channels, and the rainwater was orderly discharged into the lower Loess Tableland to eliminate the waterlogging, as shown in Table 3.

5.3. Terminal storage – integrated design of the gullies on the Loess Tableland surfaces

The discharge of rainwater in the lower Loess Tableland was the most important of the waterlogging regulation, and the mishandling will cause water and soil erosion. Thus, the planning emphasized the integrated design of the Loess Tableland surfaces and the gullies. Control the runoff on the Loess Tableland surfaces, increase the total runoff control rate in the surrounding areas of the gullies, reduce the scouring to the gullies by the surface overflows and rain and flood; delineate the protected areas in the gullies to prohibit destruction by people, and reasonably set up the discharge outlets in the lower Loess Tableland and the lower Loess Tableland project (Fig. 10). Meanwhile, carry out the project of gully reinforcing and Loess Tableland protecting, among which, the slope area mainly took biological and ecological measures, and the gully area mainly adopts ecological storage facilities. Engineering measures such as slope reinforcement and green restoration, as well as ecological measures such as setting up overflow pollution storage pools, constructed wetlands, ecological water storage ponds at the bottom of Huoxiang Gully had been taken in Huoxiang Gully (Fig. 11), which can adjust the microclimate of Huoxiang Gully, thereby preventing water and soil erosion from polluting the downstream water body,

Table 3
List of super-standard rainwater storage capacity

Project type	Super-standard rainwater storage capacity
Low impact development facilities	20%
Regional rainwater storage facilities	15%
Discharge outlets and channel ecological facilities in the lower Loess Tableland	5%
Rainwater discharged into Malian River in the lower Loess Tableland	Others

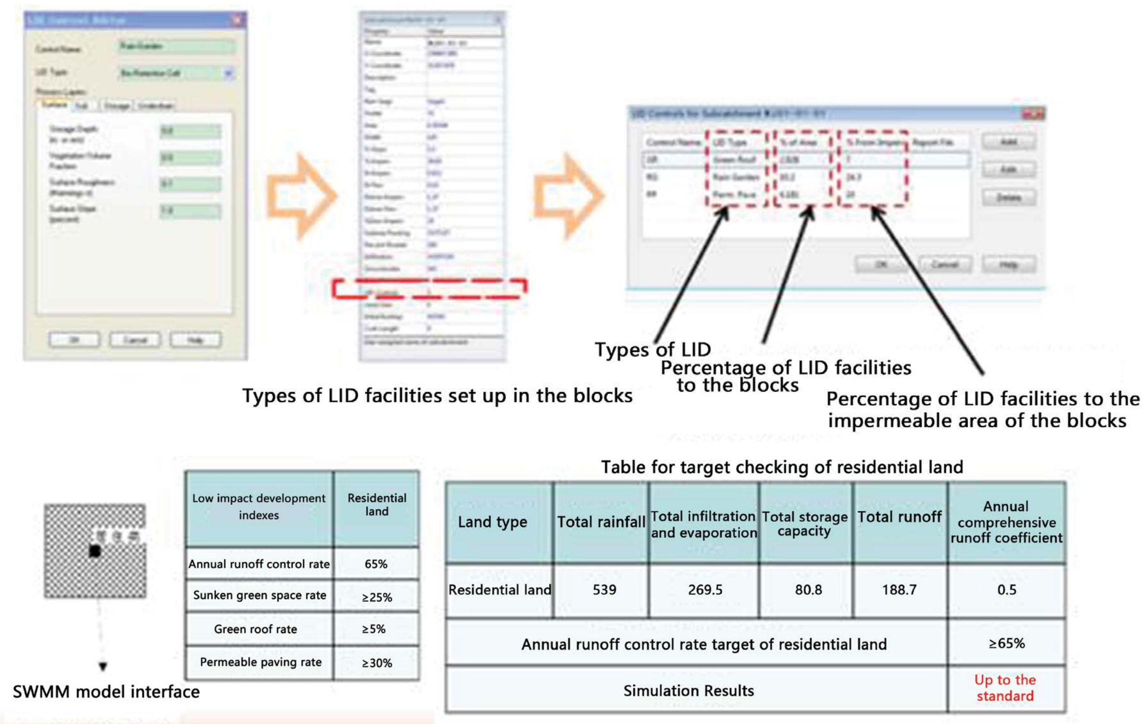

Fig. 9. Schematic diagram of the checking process of SWMM models.

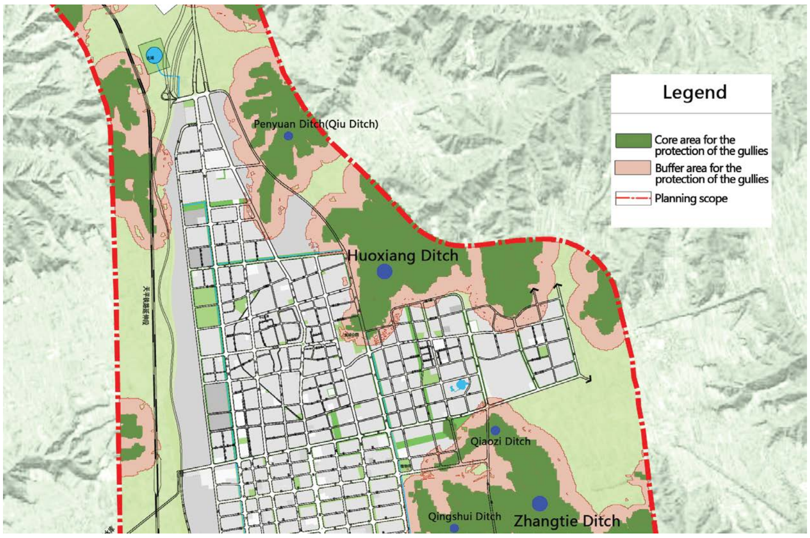

Fig. 10. Schematic diagram of protection planning of the gullies.

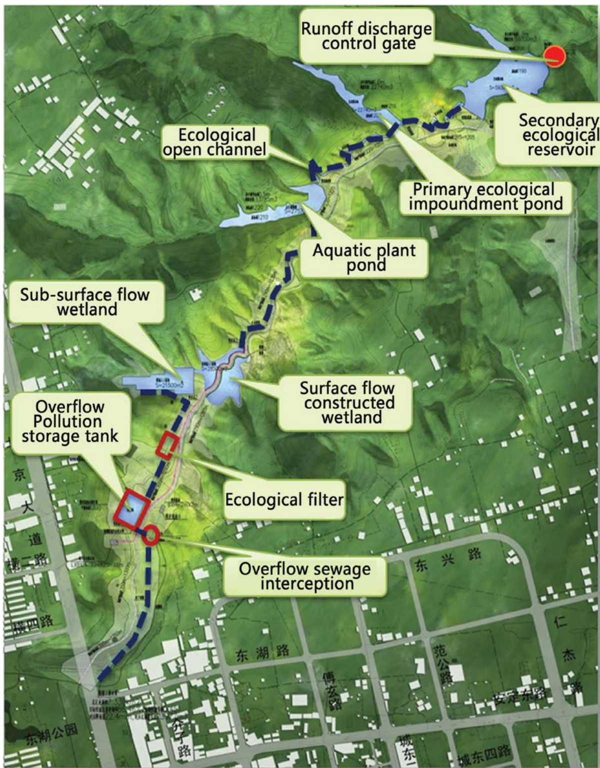

Fig. 11. Schematic diagram of regulation planning for the gullies in Huoxiang Gully.

and also can sprinkle the vegetation in Huoxiang Gully by combining the detention with storage as ecological water.

6. Conclusions

The fact that every heavy rain will bring about waterlogging has become a common problem in many cities, which directly affects the safety of life and property of the residents. Urban waterlogging not only exposes the problem of backward urban drainage facilities and low construction standards, but also reflects the fact that the modern urban construction mode of high density and high intensity brings ever-increasing damage to the urban environment. As a new concept of urban construction, the Sponge City is important for the practice of ecological civilization, and also provides a systematic solution for the waterlogging regulation. Qingyang, a pilot city of National Sponge Cities, has carried out active exploration in waterlogging regulation and soil and water conservation, and has highlighted the regional characteristics of waterlogging regulation measures. It has carried out active exploration and attempt for the Northwest China, especially the cities on the Loess Tableland.

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