Performance assessment of sponge city development at multiple scales based on 1D/2D coupled modeling and monitoring:
a case study in national pilot city

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XVIII World Water Congress
International Water Resources Association (IWRA)
XVIII WORLD WATER CONGRESS
Water for All
Harmony between Humans and Nature
第18届 世界水资源大会
水与万物：
人与自然和谐共生

Content

Sponge city development:

A new concept and related technical methodology, called "sponge city," proposed in 2013

1. Two batches national pilot cities (16+14)

2. Three batches national demonstration cities (20+25+15)

3. Systematic global promotion

606 km^2 of urban area has implemented sponge city-related construction in 30 national pilot cities and 90 provincial pilot cities, and about 10,200 km^2 of urban area will be developed or redeveloped according to sponge city requirements (data by the end of 2019)

More sponge cities "in progress"

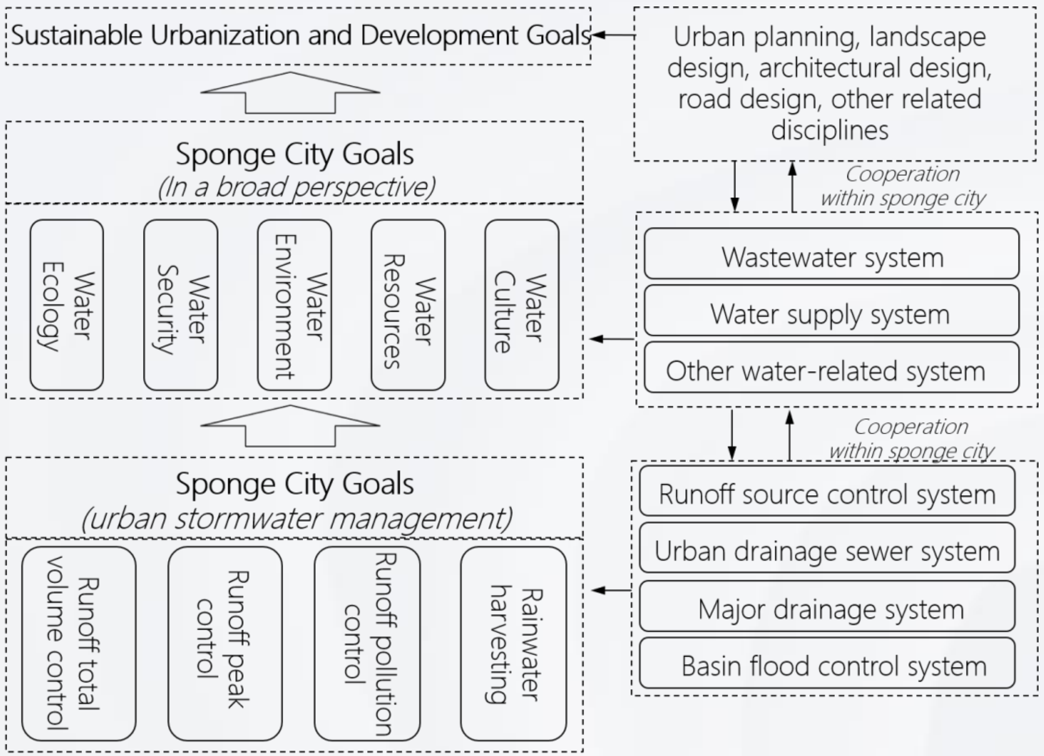


Fig. Components and goals of sponge city

1 Introduction

Stormwater management criteria :

- Includes water quantity and water quality aspects.
- For the water quantity, the criteria can be classified into four levels according to the functions of four components.

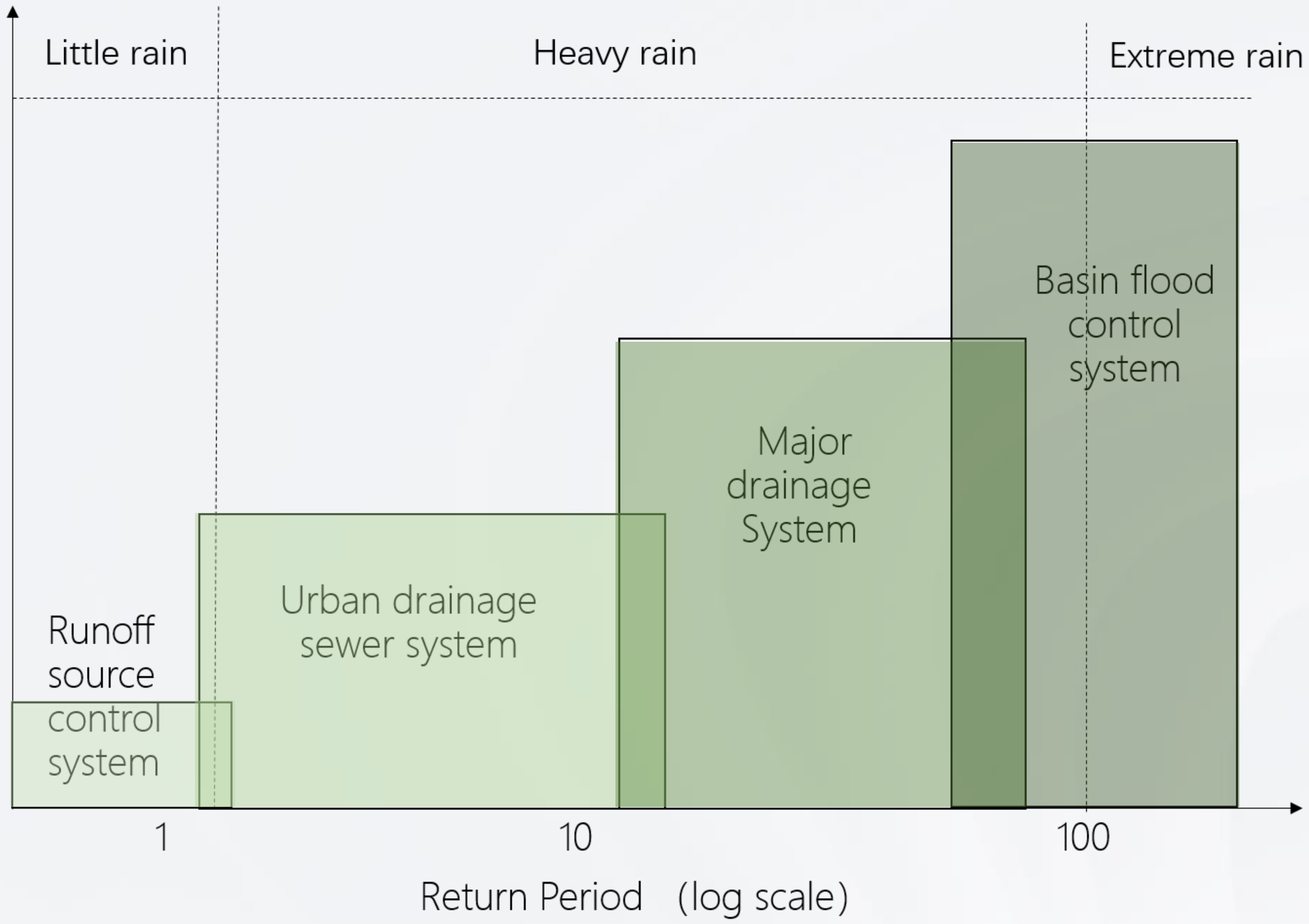
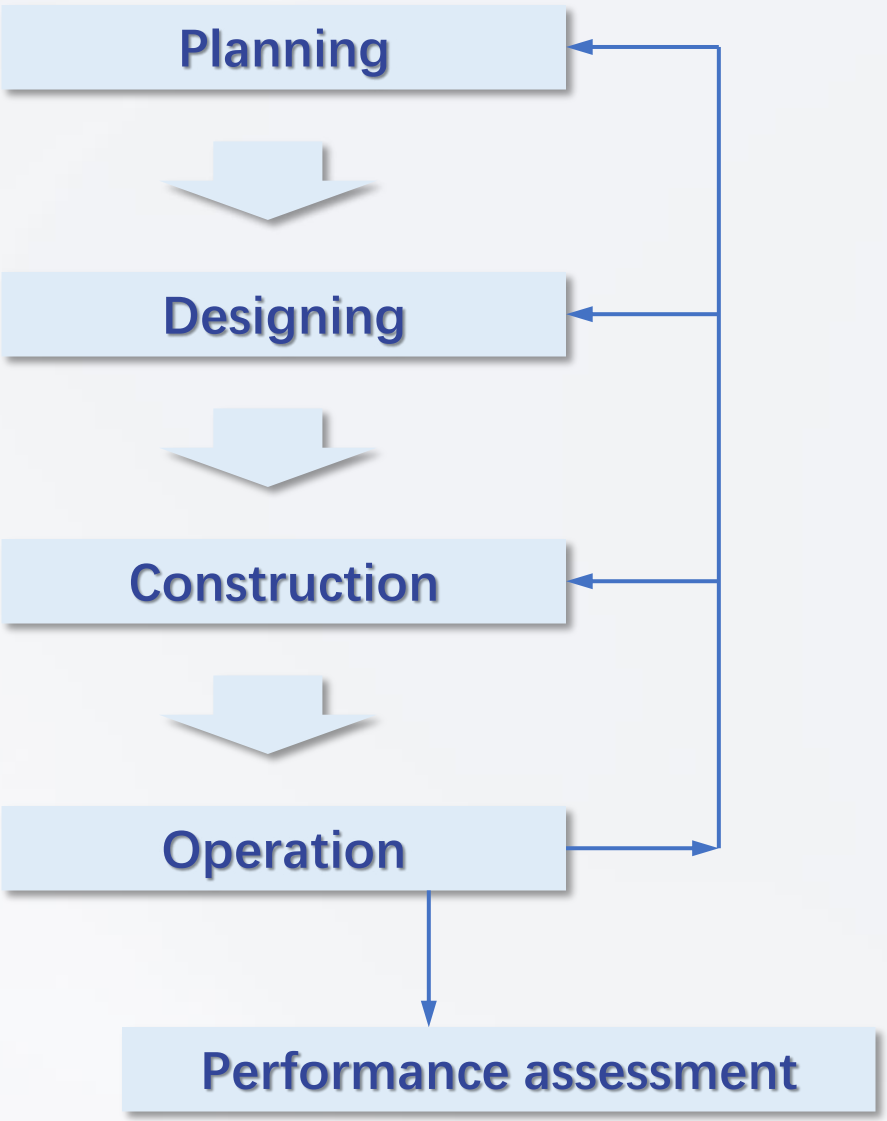


Fig. Stormwater management criteria of sponge city (water quantity)

1 Introduction



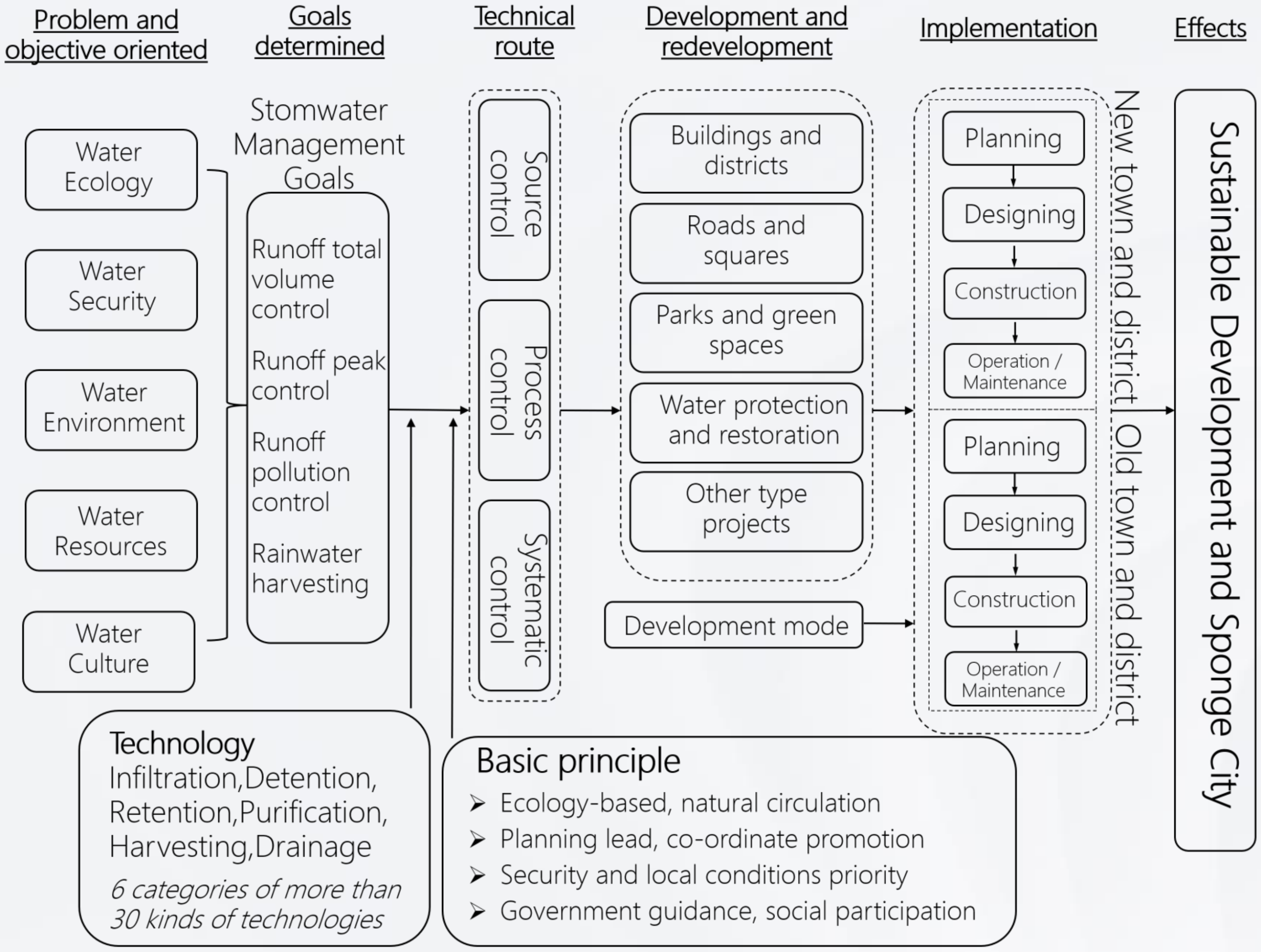


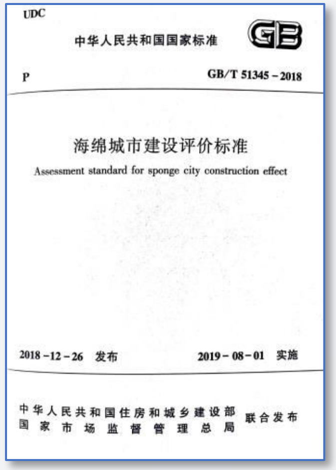
Fig. Implementation approach of sponge city development

National standard and specifications for **SPONGE CITY DEVELOPMENT**:


海绵城市建设技术指南
——低影响开发雨水系统构建
（试行）
住房城乡建设部
2014 年 10 月


UDC
中华人民共和国国家标准 GB
P GB 51174－2017
城镇雨水调蓄工程技术规范
Technical code for urban stormwater detention and retention engineering
2017－01－21 发布 2017－07－01 实施
中华人民共和国住房和城乡建设部
中华人民共和国国家质量监督检验检疫总局 联合发布


UDC
中华人民共和国国家标准 GB
P GB 51222－2017
城镇内涝防治技术规范
Technical code for urban flooding prevention and control
2017－01－21 发布 2017－07－01 实施
中华人民共和国住房和城乡建设部
中华人民共和国国家质量监督检验检疫总局 联合发布


UDC
中华人民共和国国家标准 GB
P GB/T 51345－2018
海绵城市建设评价标准
Assessment standard for sponge city construction effect
2018－12－26 发布 2019－08－01 实施
中华人民共和国住房和城乡建设部
国家市场监督管理总局 联合发布


GB
中华人民共和国国家标准
GB/T 39599—2020
低影响开发雨水控制利用　基础术语
Low impact development stormwater management and harvest—Basic terminology
国家市场监督管理总局
国家标准化管理委员会 发布


GB
中华人民共和国国家标准
GB/T 38906—2020
低影响开发雨水控制利用　设施分类
Low impact development stormwater management and harvest—Facility classification
国家市场监督管理总局
国家标准化管理委员会 发布


GB
中华人民共和国国家标准
GB/T 42111—2022
低影响开发雨水控制利用
设施运行与维护规范
Low impact development stormwater management and harvest—Specification for facility operation and maintenance
国家市场监督管理总局
国家标准化管理委员会 发布

2014
TECHNICAL GUIDE TO SPONGE CITY CONSTRUCTION

2017
TECHNICAL CODE FOR URBAN STORMWATER DETENTION AND RETENTION ENGINEERING (GB 51174-2017)

TECHNICAL CODE FOR URBAN FLOODING PREVENTION AND CONTROL (GB 51222-2017)

2018
ASSESSMENT STANDARD FOR SPONGE CITY CONSTRUCTION (GB/T 51345-2018)

2020
LOW IMPACT DEVELOPMENT STORMWATER MANAGEMENT AND HARVEST—BASIC TERMINOLOGY（GB/T 39599-2020）

LOW IMPACT DEVELOPMENT STORMWATER MANAGEMENT AND HARVEST—FACILITY CLASSIFICATION（GB/T 38906-2020）

2022
LOW IMPACT DEVELOPMENT STORMWATER MANAGEMENT AND HARVEST—SPECIFICATION FOR FACILITY OPERATION AND MAINTENANCE（GB/T 42111-2022）

1 Introduction

《Assessment Standard for Sponge City Effects》(GB/T 51345-2018)

ITEMS

ELEMENTS

1. Volume capture ratio of annual rainfall and runoff volume control

New development areas

- Volume capture ratio
- Runoff volume control

Re-development areas

- Volume capture ratio
- Runoff volume control

2. Implementation effectiveness of the source reduction project

Residential area

- Volume capture ratio of annual rainfall
- Runoff volume control
- Runoff pollution control
- Peak runoff control
- Impervious land surface ratio

Roads, parking lots, open squares

- Volume capture ratio of annual rainfall
- flood prevention and drainage functions
- Runoff pollution
- Runoff volume control
- Peak runoff control

Park and protective green space

- Runoff volume control
- Receive runoff

3. Road surface ponding and local flood control

Grey and green infrastructure

- Detention
- Reduction
- Peak runoff control

Minor drainage system

- No surface ponding
- Design storm events

Major drainage system

- No local flooding
- Design storm events

4. Urban water quality

Grey and green infrastructure

- Runoff pollution
- CSOs
- Water quality purification

During dry weather conditions

- No sewage
- No wastewater directly discharge

During wet weather conditions

- mis-connections
- CSOs
- SS concentration

No malodorous waterbody

- Transparency
- Dissolved oxygen
- Ammonia nitrogen

Water quality after installing

- Water quality before Sponge City infrastructure is installed

ITEMS

ELEMENTS

5. Natural ecological pattern management and shoreline for ecology conservation

The surface area of natural waterbodies

- Natural flood channels
- Flood plains
- Ecologically sensitive areas

The ecological shoreline of the urban water bodies

- New and redevelopment
- Production and necessary
- Flood control and protection

6. Variation trend of the groundwater depth

Annual average groundwater phreatic level

- The descending trend should be alleviated

7. Urban heat island effect mitigation

The average daily temperature

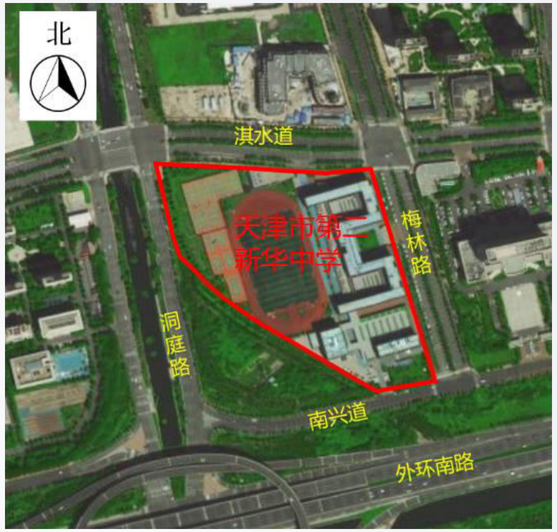
- Urban areas
- Surrounding suburbs
- Summer seasons (June to September)
- The same period in history
- Subtracting natural temperature variation impacts

Zoning map of volume capture ratio of annual rainfall in China

2 Materials and methods

DongTingLu Drainage Basin (DTL)
Typical Drainage Basin Project

- 3.24 km^2, located on the south side of the downtown area of Tianjin
- Mixing old and new communities
- the sewer network in this drainage basin has no hydraulic connection with other sewer systems nearby, the boundaries are clearer and independent



Second Xinhua Middle School (XH)
Typical community project

- 5.4 ha, Located southwest of the DTL drainage basin
- New public building project
- Sunken green space, permeable paving, rainwater buckets, dry streams, rainwater reservoirs, grass ditches

2 Materials and methods

Second Xinhua Middle School
Typical community project

No	Practices	Practice number	Scale
1	Grass swale	9	2670 m^2
2	Sunken green space	13	922.2 m^2
3	Permeable brick paving	/	3110 m^2
4	Dry creek	1	1345 m^2
5	Rainwater retention tank	3	969.71 m^3
6	Rainwater barrel	4	4000 L
7	Rain tree infiltration	4	4
8	Permeable concrete paving	/	5900 m^2
9	bioretention	1	207.8 m^2


Permeable brick paving


Dry creek


Sunken green space


Permeable concrete paving


Rainwater barrel


Green roof


Grass swale

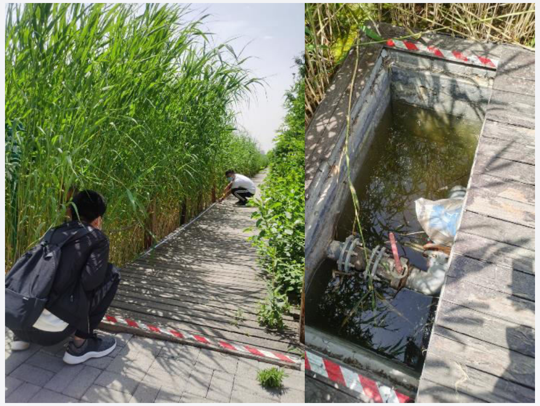

Rainwater retention tank

2 Materials and methods

DongTingLu Drainage Basin Typical Drainage Basin Project

Constructed wetland





Stormwater pump station



Sponge road & sponge community



2 Materials and methods

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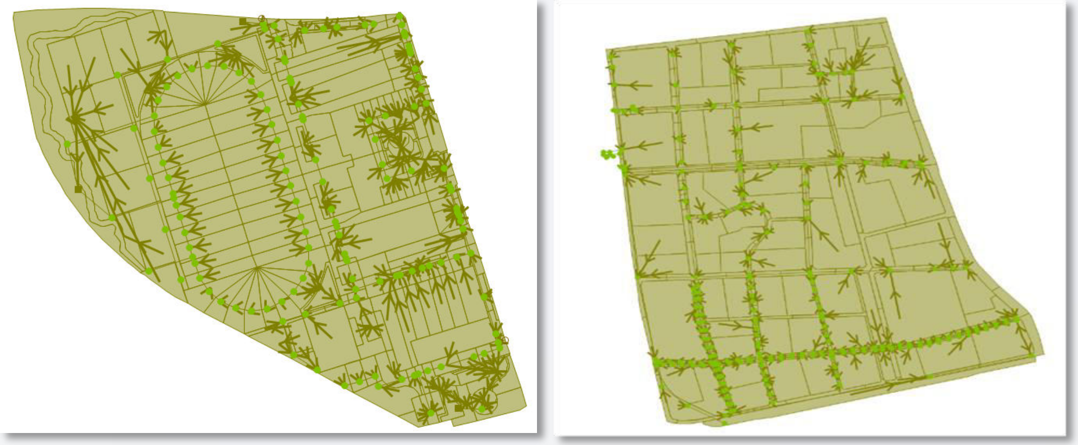
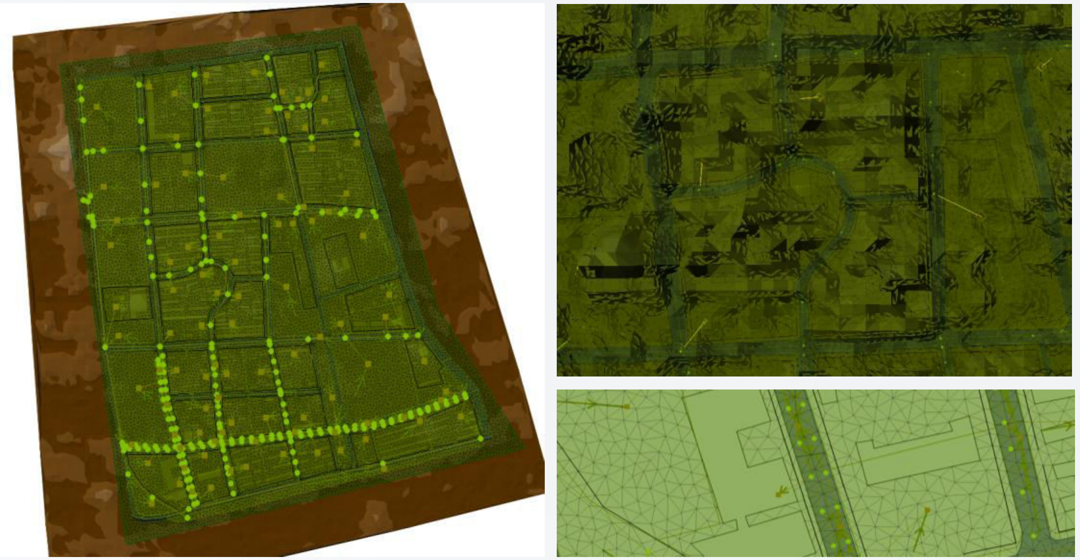
International Water Resources Association (IWRA)

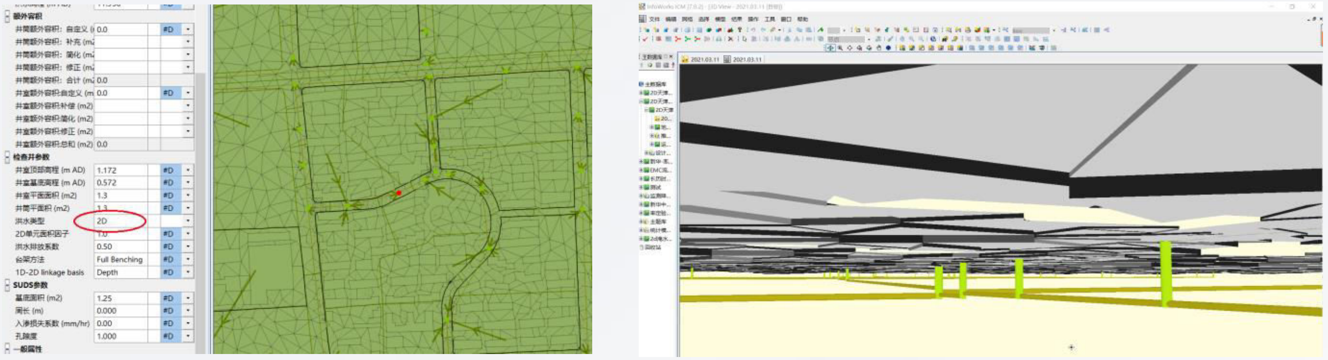
Drainage model establishment



One-dimensional sewer model

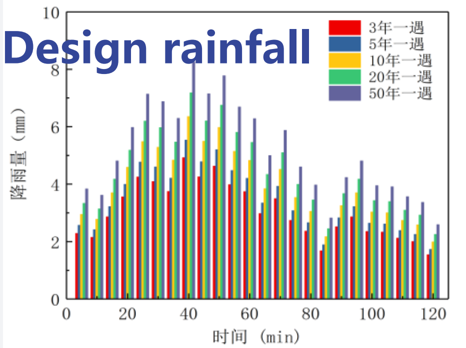


Two-dimensional overflow model

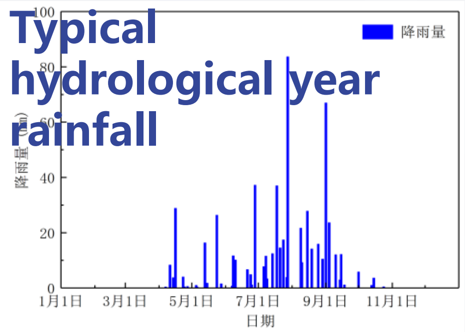


1D/2D model coupling

Design rainfall



Typical hydrological year rainfall



InfoWorks ICM

DTL drainage basin model:
- Sub-catchment: 287
- Sewer/ conduit: 229
- Manhole/ node: 233

XH community model:
- Sub-catchment: 233
- Sewer/ conduit: 141
- Manhole/ node: 140

2 Materials and methods

Field monitoring

Surface runoff sampling

Stormwater sewer runoff sampling

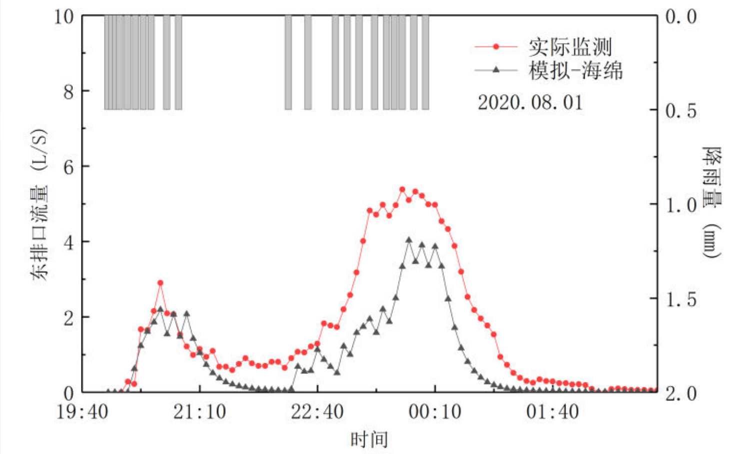
Stormwater practice monitoring

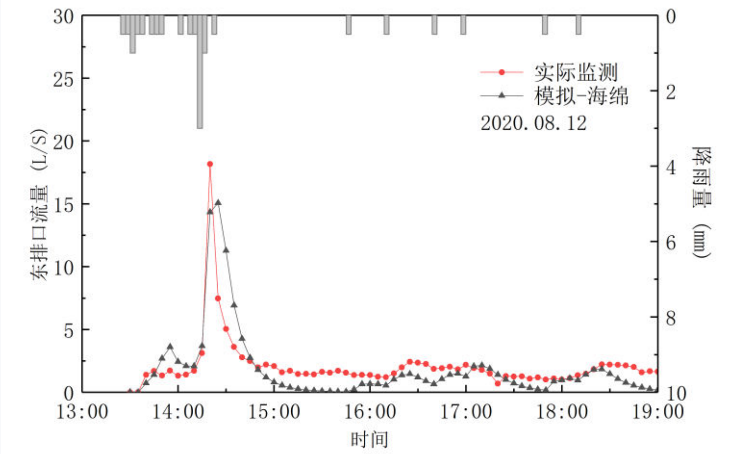
Monitoring period: June to August 2020

Rainfall events monitored: 20 rainfall events were monitored, including 4 heavy rain, 8 moderate rain and 8 light rain

Monitoring items: rainfall depth, flow rate, SS, COD, TN, TP

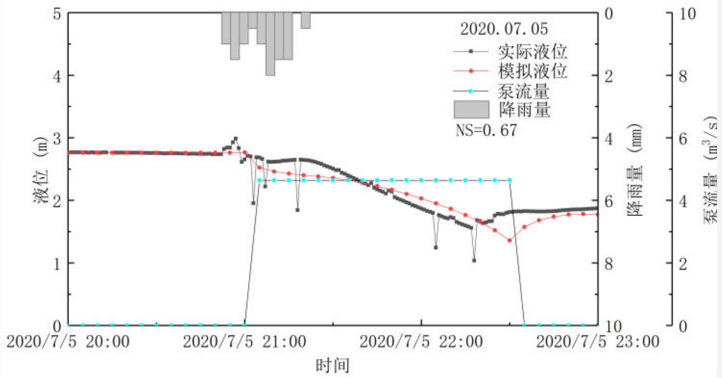
Model calibration and verification

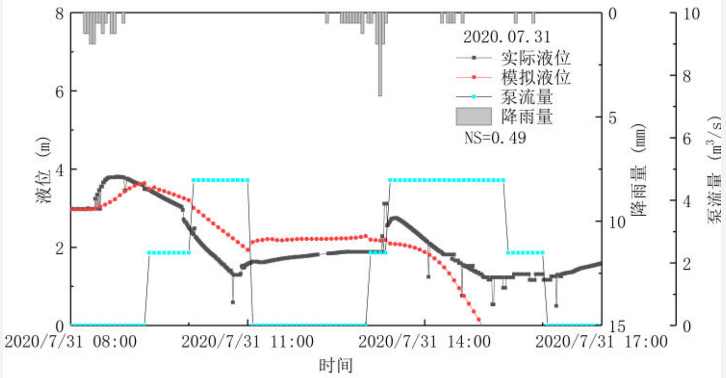


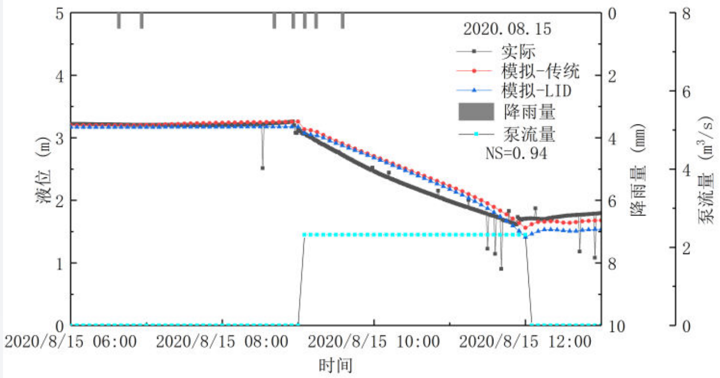


XH community

DTL drainage basin







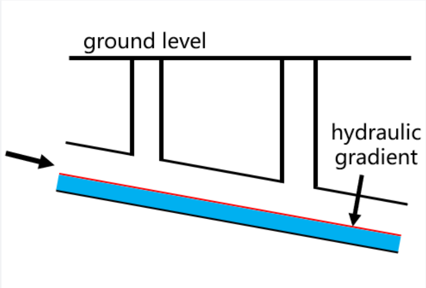
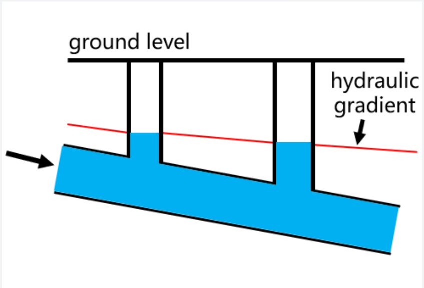
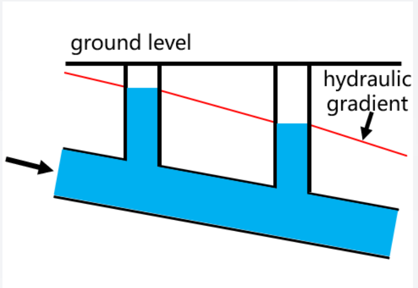
Nash-Sutcliffe efficiency coefficient for all the events were higher than 0.5

The Model calibration and verification results meet the requirements in Chinese national standard GB/T 51345

2 Materials and methods

Performance assessment methods

Surcharge State (K value)

K < 1	Pipe is not surcharged. The water level is below the soffit level at both ends of the pipe. Surcharge State is calculated as the ratio of water depth to pipe height.	
K=1	Water level at the upstream and / or downstream end of the pipe is above the soffit level, and the flow is less than or equal to the pipe's full capacity.	
K=2	Water level at the upstream and / or downstream end of the pipe is greater than the soffit level, and the flow is greater than the pipe's full capacity.	

(1) Total volume capture ratio (α)

$$\alpha = \frac{10HA - V_p}{10HA} \times 100\%$$

Where V_p - total runoff from the system outlet (m^3)

(2) Peak runoff control ratio (F)

$$F = \frac{F_t - F_s}{F_t} \times 100\%$$

Where F_t - peak flow rate at discharge point of traditional construction mode, (m^3/s)

F_s - peak flow rate at discharge point after sponge transformation, (m^3/s)

(3) Total pollutant reduction ratio (M)

$$M = \frac{m_t V_t - m_s V_s}{m_t V_t} \times 100\%$$

Where m_t - Concentration of pollutants at the system outfall of the traditional construction mode (mg/L)

V_t - total volume of water discharged at the system outlet of the traditional construction mode (m^3)

m_s - the concentration of pollutants at the system outlet after sponging modification (mg/L)

V_s - total volume of water discharged at the system outlet after sponging modification (m^3)

3 Results and discussion

3.1 Stormwater management performance under the design rainfall conditions modeling

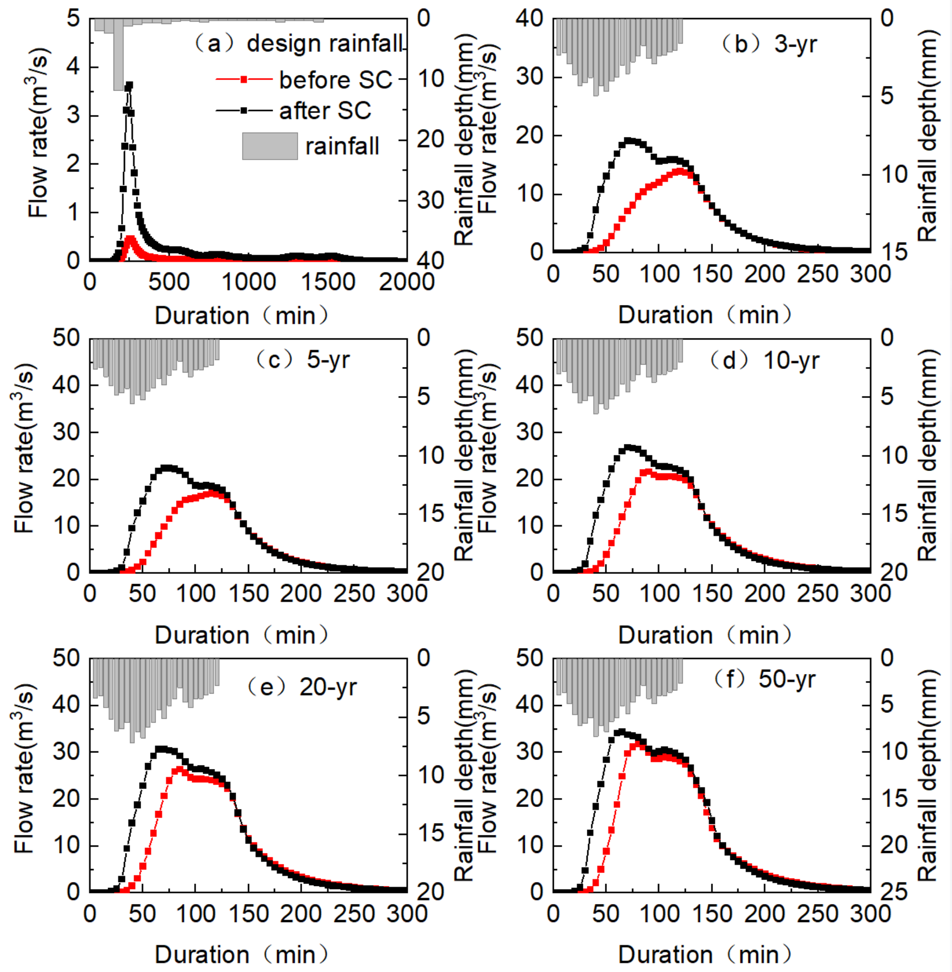
3.2 Runoff volume and pollution control performance by long term modeling for typical hydrological years

3.3 Discussion on volume capture ratio of annual rainfall

3.1 Stormwater management performance under the design rainfall conditions modeling

DTL Drainage Basin: Flow process

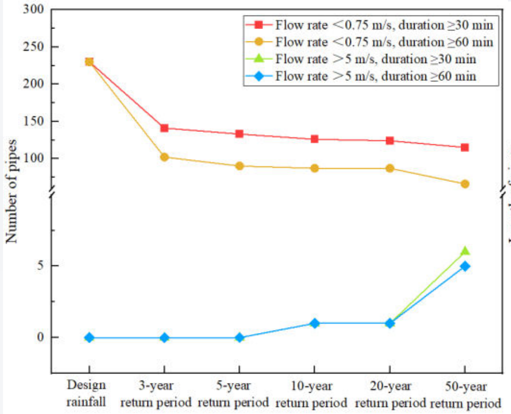
- For the design rainfall, the runoff appear time was delayed by 20 minutes and the peak time was delayed by 10 minutes, and the peak flow reduction rate reached 87.09% ;
- For 3-year, 5-year, 10-year, 20-year and 50-year rainfall conditions, the runoff appear time was delayed more than 5 minutes, and the peak flow rate was delayed by 15-50 minutes.
- With the increase of rainfall return period, the runoff reduction rate of DTL drainage basin decreases gradually.
- After sponge city redevelopment, the sensitivity of the flow rate to rainfall is significantly reduced.



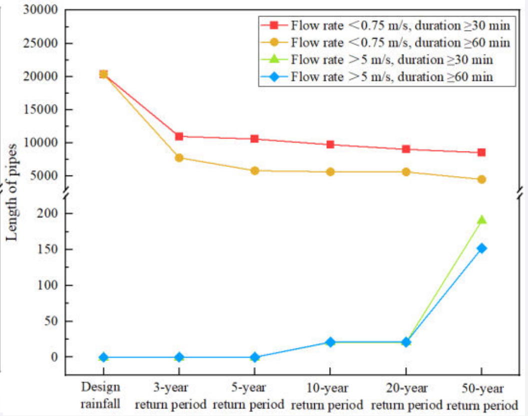
3 Results and discussion

3.1 Stormwater management performance under the design rainfall conditions modeling

DTL Drainage Basin： velocity distribution analysis, Traditional approach vs. sponge city approach



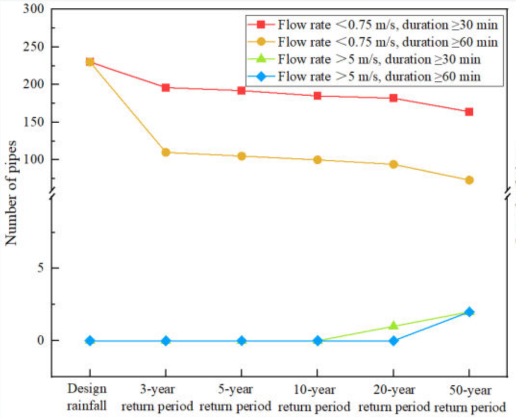
(a) Number of pipes



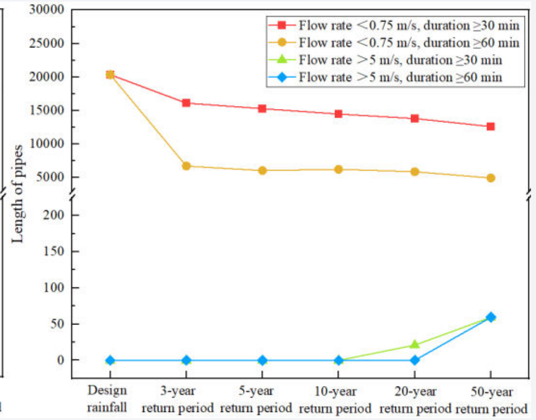
(b) Length of pipes

Traditional construction pattern

- With the increasing rainfall return period, the number and length of pipes with low flow rate and short duration show a decreasing trend, while the number and length of pipes with high flow rate and long duration show an increasing trend.
- The drainage capacity of pipes under the sponge city construction pattern is significantly improved compared with the traditional construction pattern, with a higher proportion of pipes with low flow rate and short duration, and a lower proportion of pipes with high flow rate and long duration.



(a) Number of pipes



(b) Length of pipes

Sponge city construction pattern

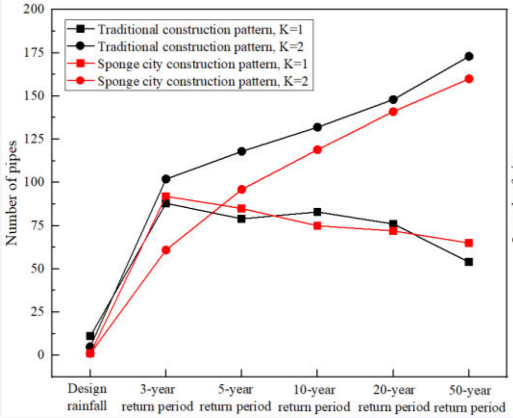
Traditional construction pattern

Sponge city construction pattern

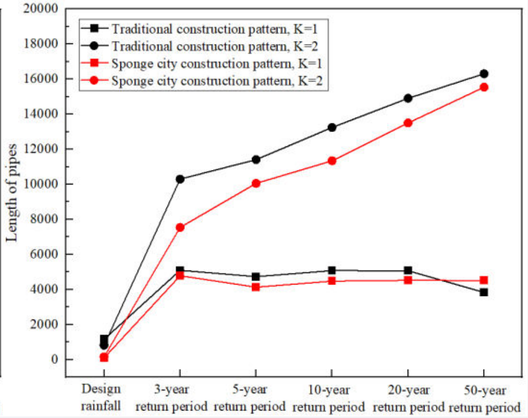
3 Results and discussion

3.1 Stormwater management performance under the design rainfall conditions modeling

DTL Drainage Basin: K value analysis

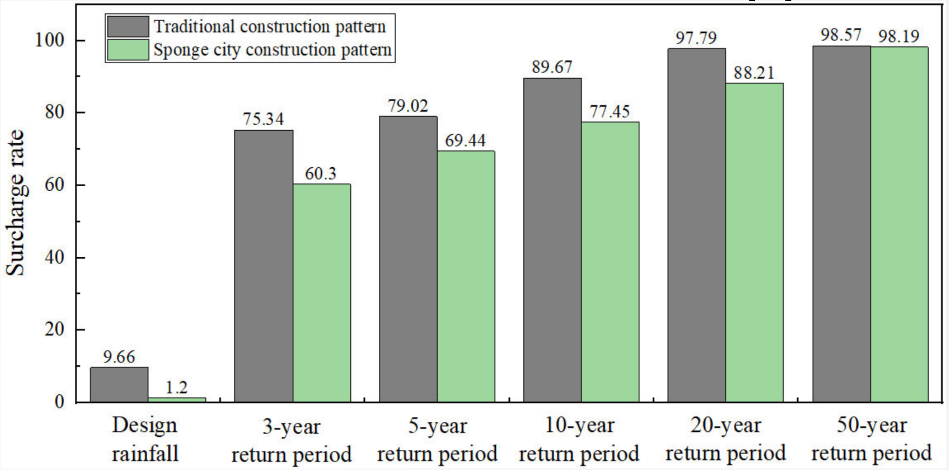


Trends in the number of pipes



Trends in the length of pipes

- With the increasing rainfall return period, the number and length of pipes at the "K=1" surcharge state show a decreasing trend, and the number and length of pipes at the "K=2" surcharge state show an increasing trend.
- After the construction of sponge city, there was a certain degree of decline in the number and length of pipelines at the surcharge state both of "K=1" and "K=2", and the surcharge rate of pipes was reduced.



Trends in the surcharge rate of pipes

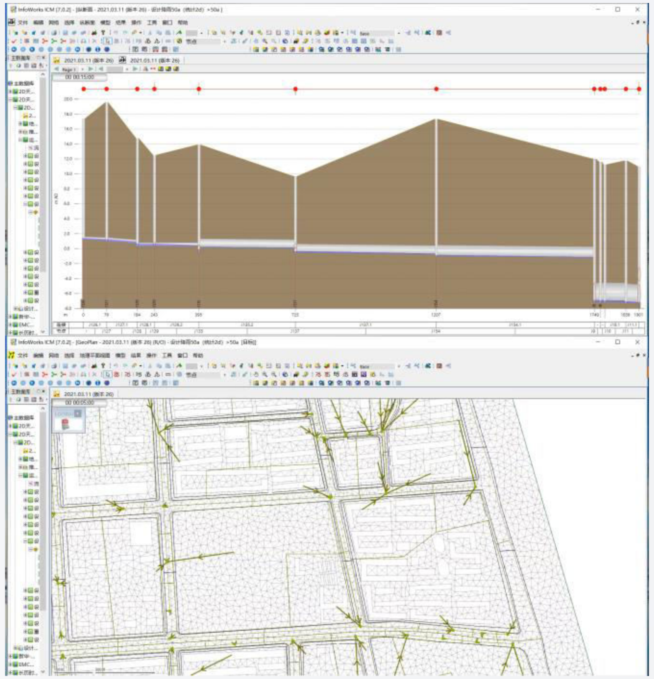
Traditional construction pattern

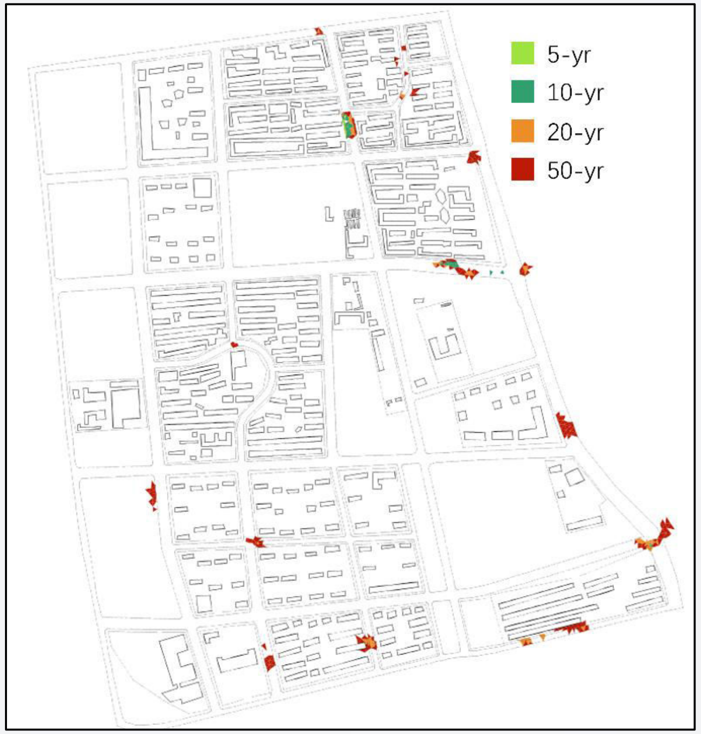
Sponge city construction pattern

3 Results and discussion

3.1 Stormwater management performance under the design rainfall conditions modeling

DTL Drainage Basin： flooding risk analysis





Sponge city redevelopment

- Sponge city redevelopment can obviously reduce the urban flooding risk
- 3-year, 5-year design rainfall, no urban flooding risk after sponge city redevelopment
- Flooding risk area reduce 67.24%, 65.62%, and 56.76% for 10-year, 20-year and 50-year rainfall conditions

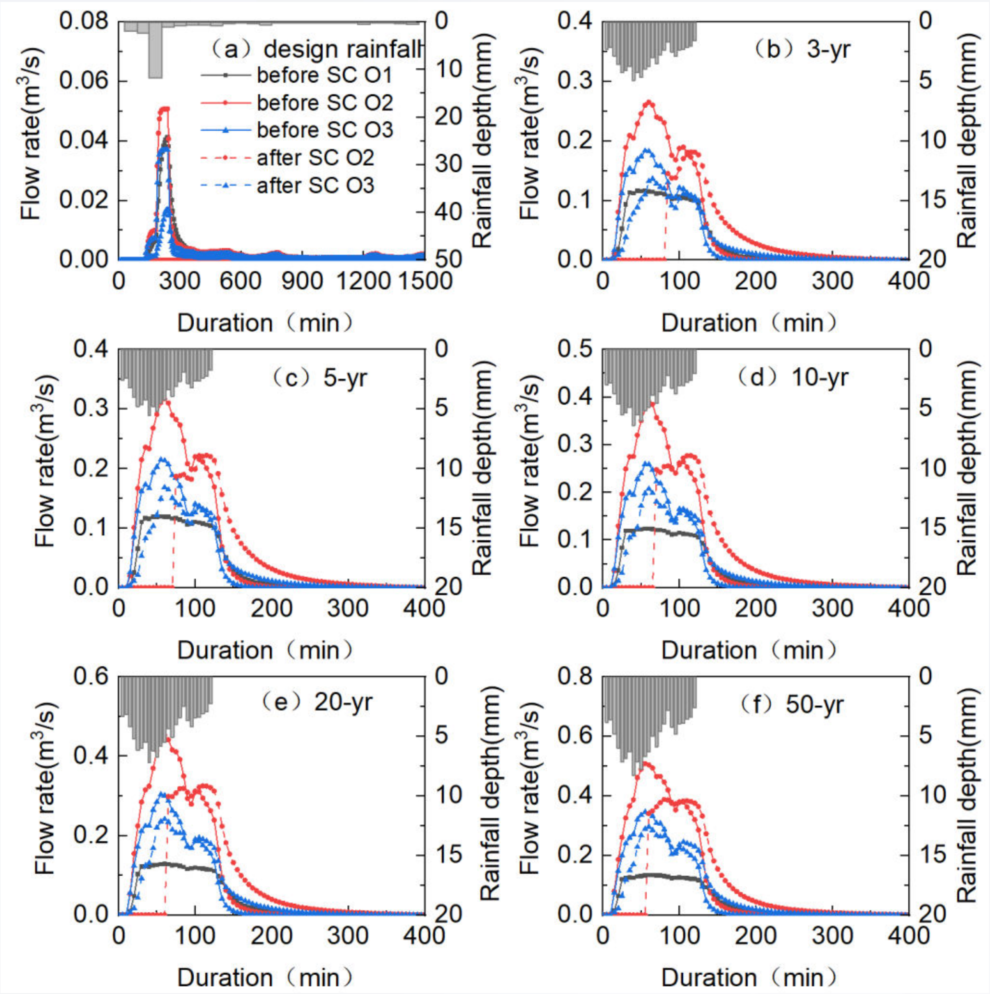
3.1 Stormwater management performance under the design rainfall conditions modeling

XH community project：Flow process

– For the design rainfall, the runoff appear was delayed by 10 minutes and the peak appear time was consistent with traditional approach, and the peak flow reduction rate reached 50%

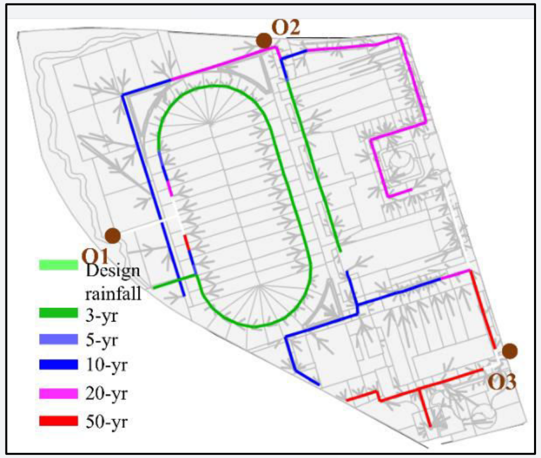
– the runoff appear was delayed 65min，60min，55min，50min and 50min, for 3-year, 5-year, 10-year, 20-year and 50-year rainfall conditions

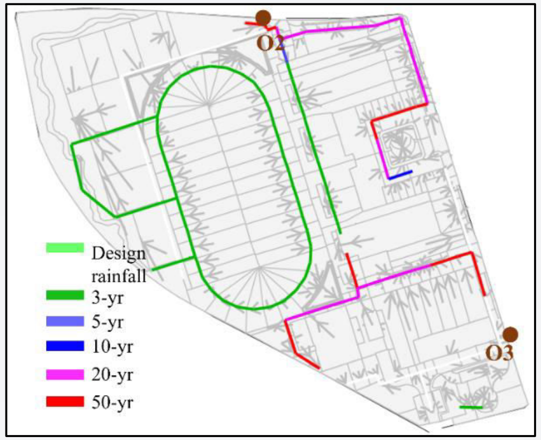
– A obvious runoff peak reduction through sponge city redevelopment



3.1 Stormwater management performance under the design rainfall conditions modeling

XH community project： velocity distribution analysis, K value analysis

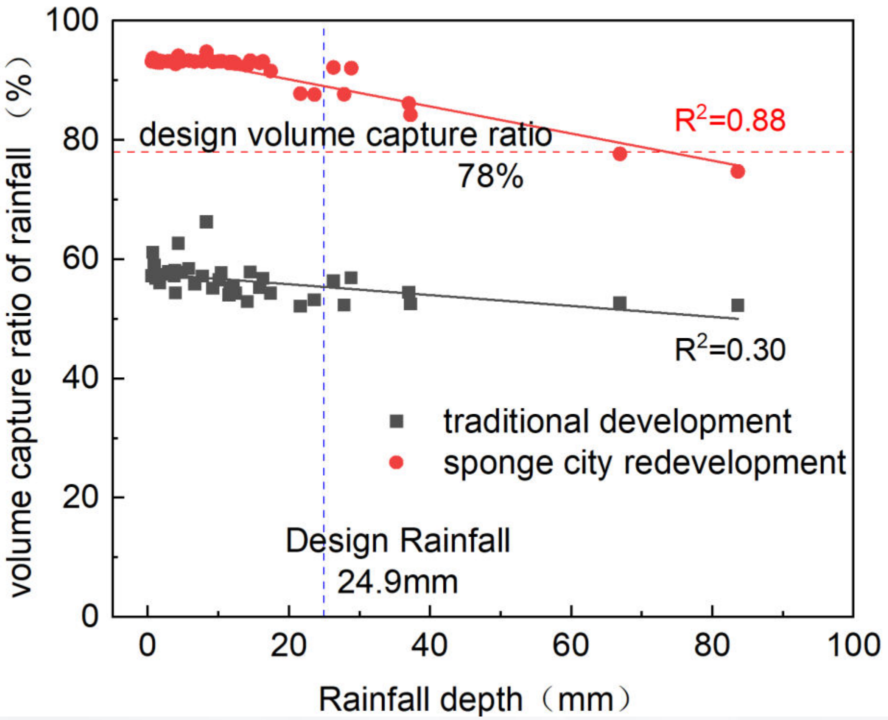




3.2 Runoff volume and pollution control performance by long-term modeling for typical hydrological year

Volume capture ratio of annual rainfall

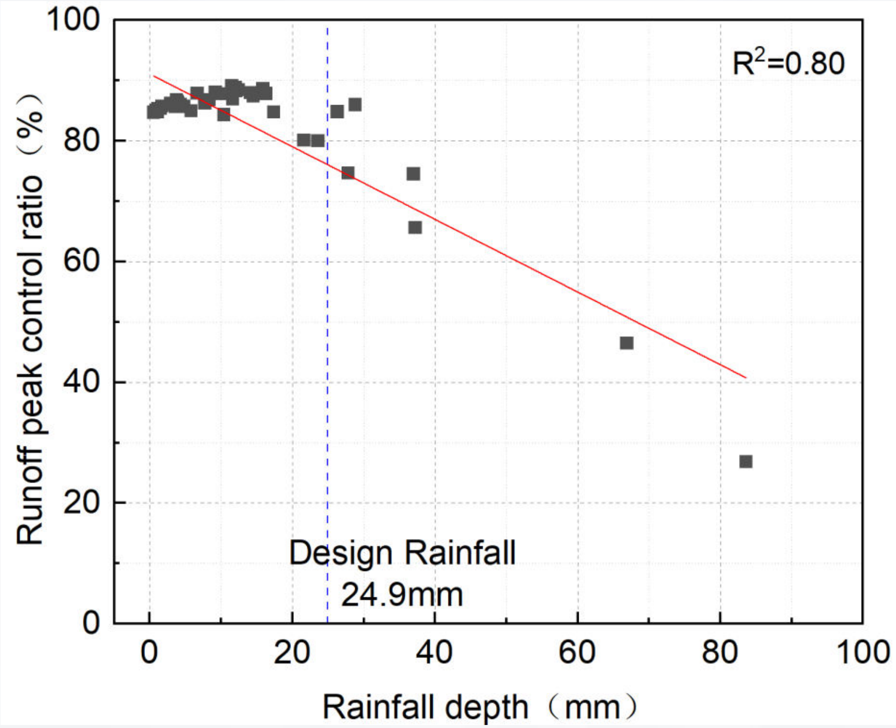
- For events less than the design rainfall (24.90 mm), the volume capture ratio of rainfall was higher than 87.66%, even in the event of heavy rainfall (83.60 mm), the volume capture ratio of rainfall also reached 77.97%
- After sponge city redevelopment, the volume capture ratio of rainfall showed a better correlation with rainfall depth, and it can be predicted the rainfall depth， it is a feasible approach
- The volume capture ratio of rainfall in XH community reached 85.7%
- The volume capture ratio of rainfall After sponge city redevelopment, the volume capture ratio of rainfall in DTL drainage basin reached 87%, meeting the target of 78% of the local planning requirements



3.2 Runoff volume and pollution control performance by long-term modeling for typical hydrological year

Runoff peak control

- As rainfall increases, the runoff peak control ratio decreases gradually;
- For events less than the design rainfall (24.90 mm), the runoff peak control ratio was higher than 80.01%
- Even in the event of heavy rainfall (83.60 mm), the runoff peak control ratio also reached 26.86%
- Runoff peak control ratio also showed a satisfied correlation with rainfall depth, and it provide a approach to predict runoff peak control ratio by rainfall depth



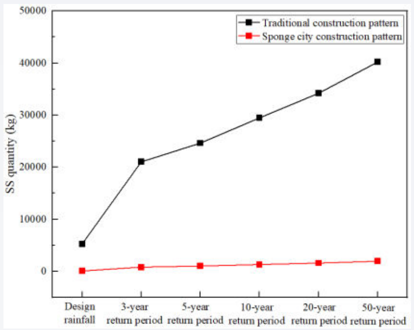
3 Results and discussion

3.2 Runoff volume and pollution control performance by long-term modeling for typical hydrological year

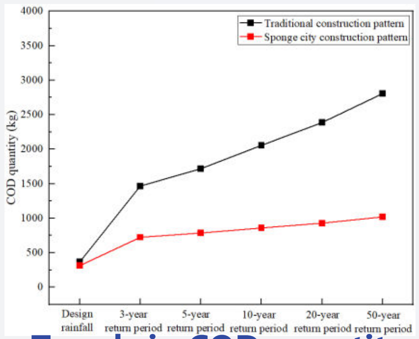
Runoff pollution control rate, DTL drainage basin, design rainfall vs. Long-term modeling

– Design rainfall modelling —— DTL drainage basin

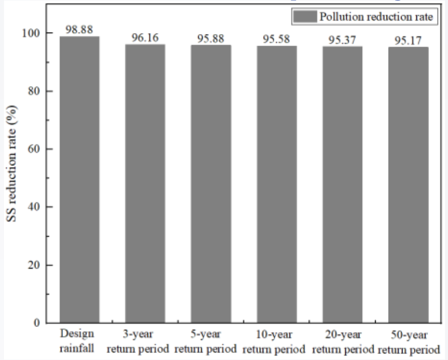
The sponge city construction played a significant role in the pollution reduction of both SS and COD in DTL subcatchment under design rainfall condition.



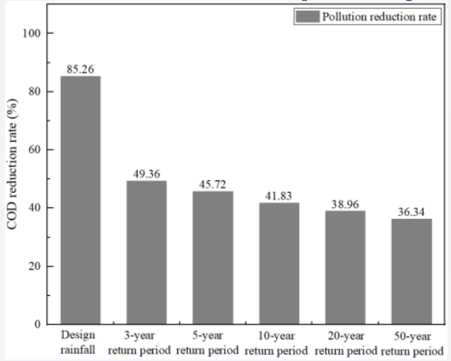
Trends in SS quantity



Trends in COD quantity



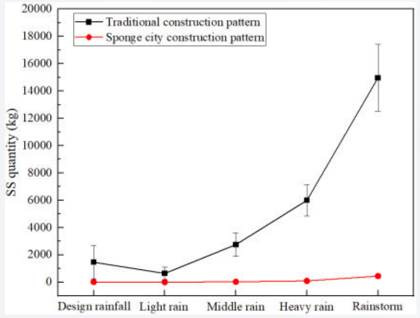
Trends in SS reduction rate



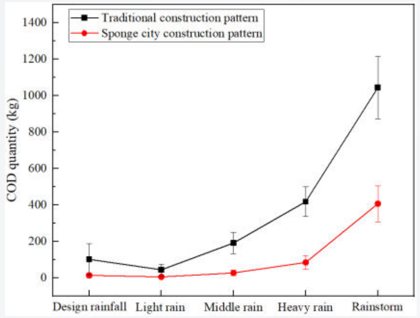
Trends in COD reduction rate

– Long-term continuous modelling—— DTL drainage basin

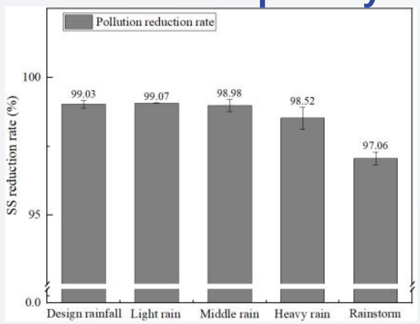
The pollution reduction of SS and COD in DTL subcatchment in a typical year was 98.32% and 77.68%.



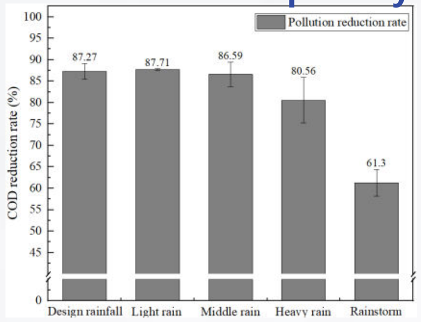
Trends in SS quantity



Trends in COD quantity



Trends in SS reduction rate



Trends in COD reduction rate

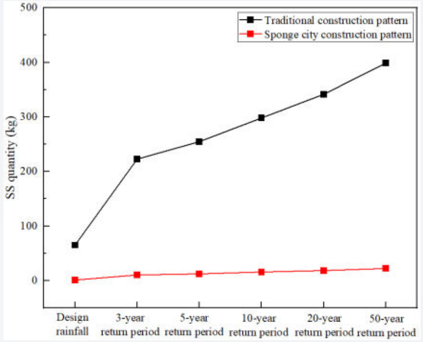
3 Results and discussion

3.2 Runoff volume and pollution control performance by long-term modeling for typical hydrological year

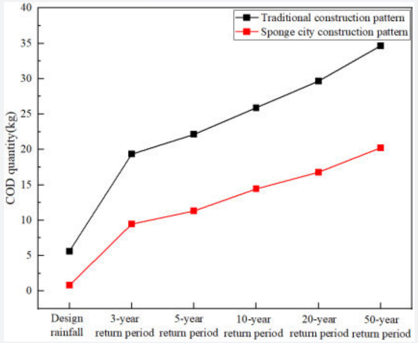
Runoff pollution control rate, XH community, design rainfall vs. Long-term modeling

– Design rainfall —— XH community

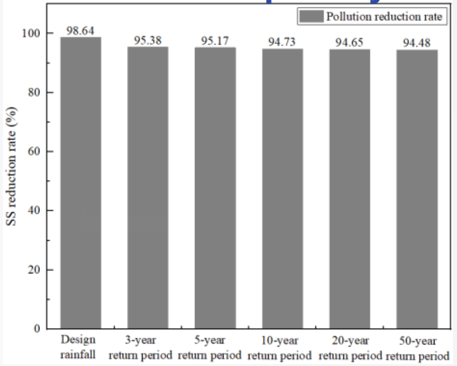
The sponge city construction played a significant role in the pollution reduction of both SS and COD in XH resident under design rainfall condition.



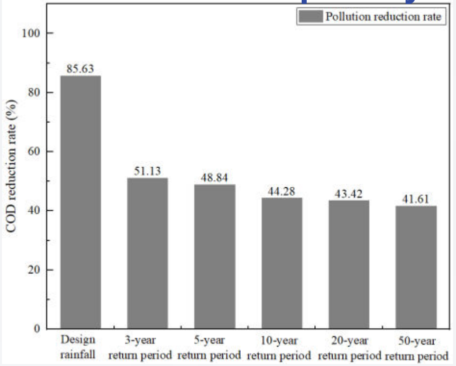
Trends in SS quantity



Trends in COD quantity



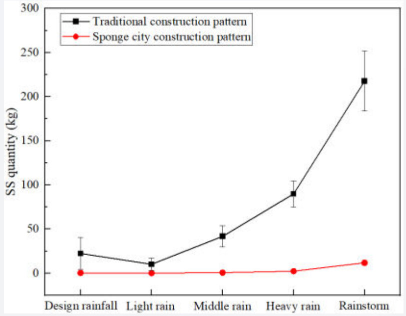
Trends in SS reduction rate



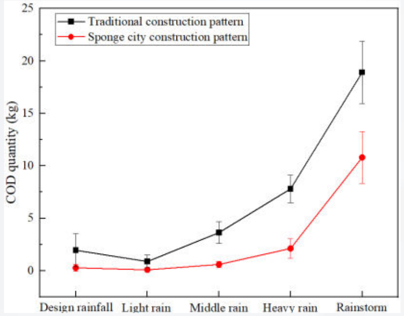
Trends in COD reduction rate

– Long-term continuous modelling—— XH community

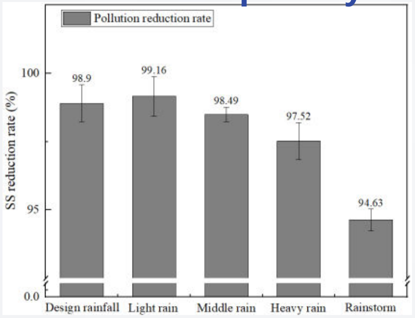
The pollution reduction of SS and COD in XH resident in a typical year was 97.67% and 75.41%.



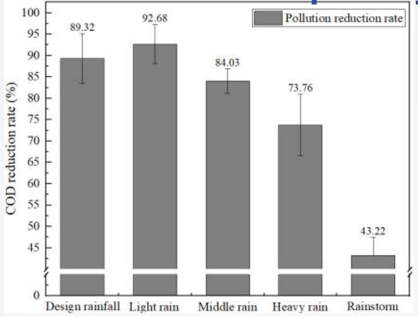
Trends in SS quantity



Trends in COD quantity



Trends in SS reduction rate

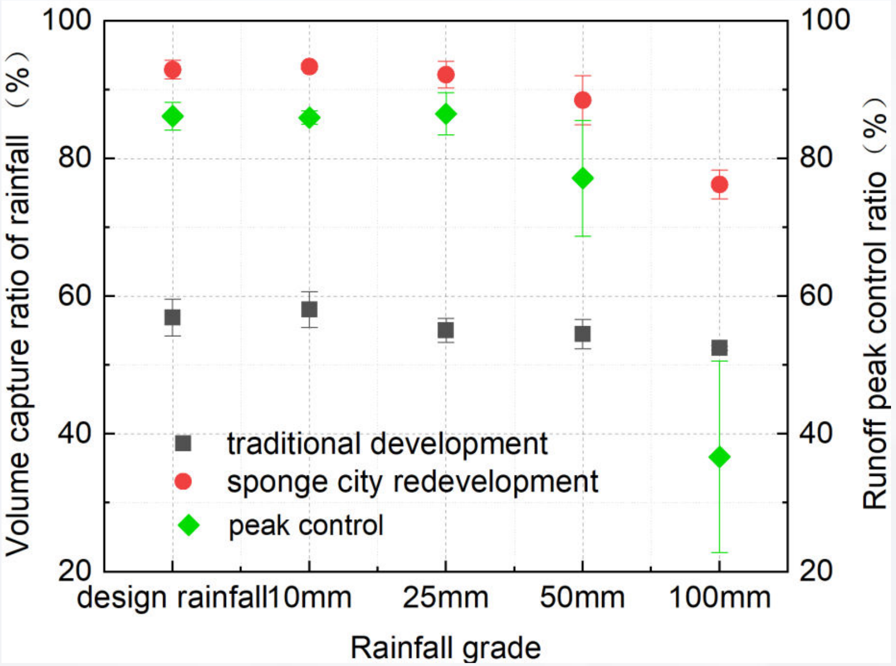


Trends in COD reduction rate

3.3 Discussion on volume capture ratio of annual rainfall

Volume capture ratio of different type rainfall events

- The **volume capture ratio of rainfall** decreases with the increase of rainfall level (from light rain to heavy rain)
- Under the traditional development mode, the **volume capture ratio of rainfall** under different rainfall levels varied slightly;
- When the rainfall depth reaches heavy rainfall level (50mm), the **volume capture ratio of rainfall was significantly reduced, but it was still higher than** 77.15%±8.42%



3.3 Discussion on volume capture ratio of annual rainfall

Runoff coefficient for a single rainfall

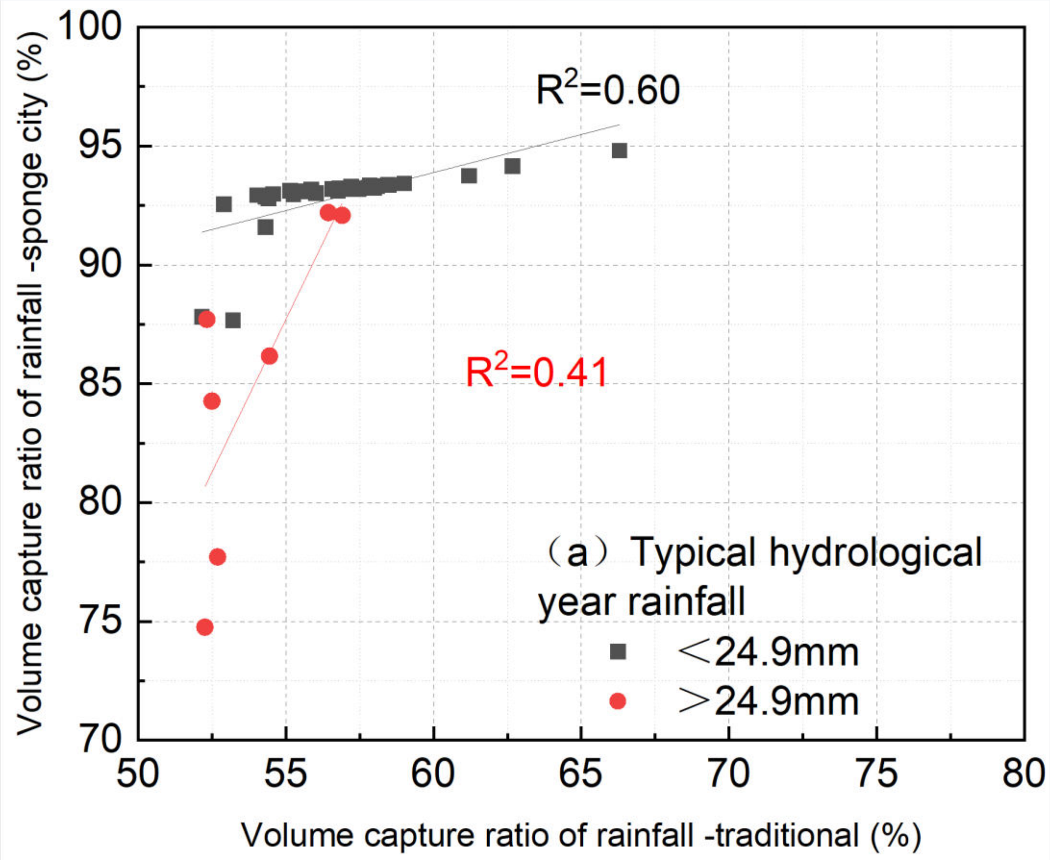
- According to the calculation method of the comprehensive runoff coefficient calculation method of the Outdoor Drainage Design Code, the **comprehensive runoff coefficient** of the DTL drainage basin is 0.63；
- The runoff coefficient of single rainfall based on long-term modeling is much lower than the theoretical calculation
- Due to the runoff control effect of stormwater management facilities in the sponge city construction, the runoff coefficient after the sponge city construction is much lower than that of the traditional approach

Rainfall level	Traditional		Sponge city	
	average	SD	average	SD
design rainfall	0.43	0.03	0.07	0.01
light rain	0.42	0.03	0.07	0.00
moderate rain	0.45	0.02	0.08	0.02
heavy rain	0.45	0.02	0.12	0.04
rainstorm	0.48	0.00	0.24	0.02
average	**0.45**		**0.13**	

3.3 Discussion on volume capture ratio of annual rainfall

Volume capture ratio of rainfall event analysis

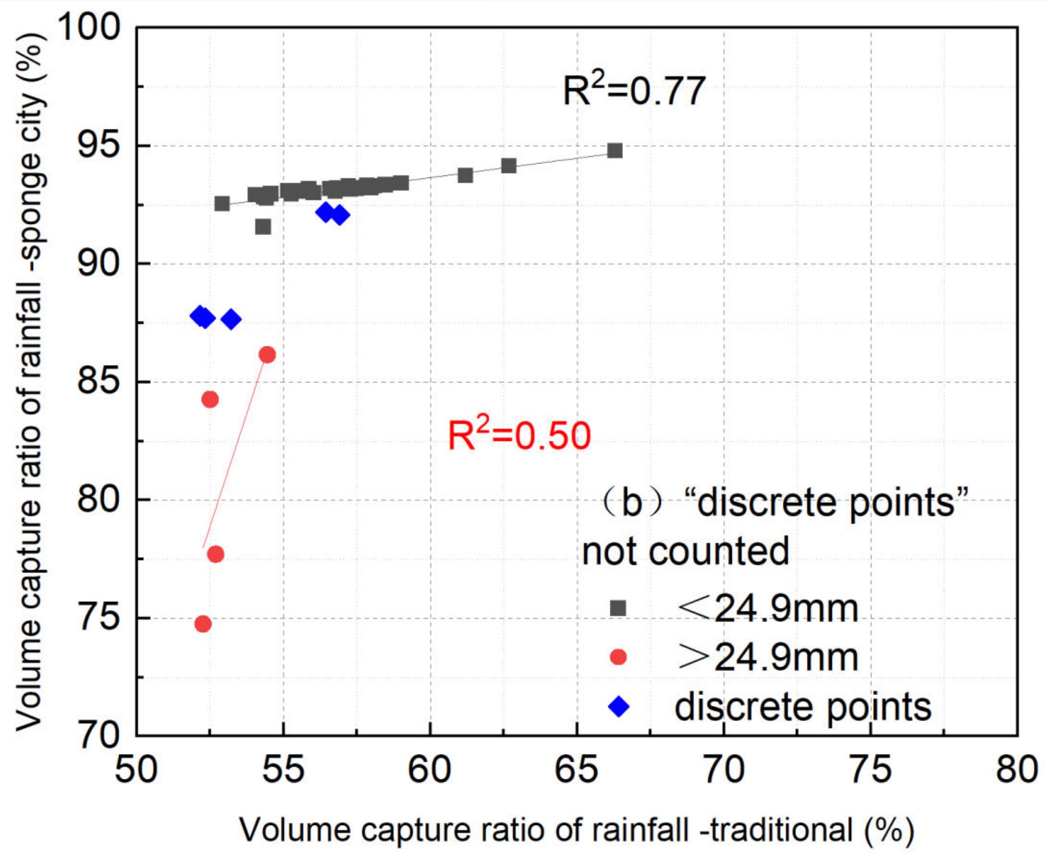
- Rainfall event where the rainfall depth is higher or lower than the designed rainfall present significantly different results
- Two types rainfall events illustrated different correlations with rainfall depths
- However, the correlation coefficient is not satisfied.



3.3 Discussion on volume capture ratio of annual rainfall

Volume capture ratio of rainfall event analysis

- Dissatisfaction occurs because there are several "discrete points"
- Concentrated in rainfall events of 24.9±5.0 mm
- Most "discrete points" was heavy rainfall event with short-duration
- If "discrete points" was not taken into account, the result will be a more satisficed
- **The results may provide a approach to predict the sponge city performance by existed traditional development conditions**



3.3 Discussion on volume capture ratio of annual rainfall

Volume capture ratio of rainfall event analysis

According to definition of **Volume Capture Ratio of Annual Rainfall** in "TECHNICAL GUIDE TO SPONGE CITY CONSTRUCTION" :

- ①24h rainfall data was used to calculate the relationship between Volume capture ratio of annual rainfall and design rainfall depth
- ② Samples lower than 2 mm (24h rainfall depth) are not counted

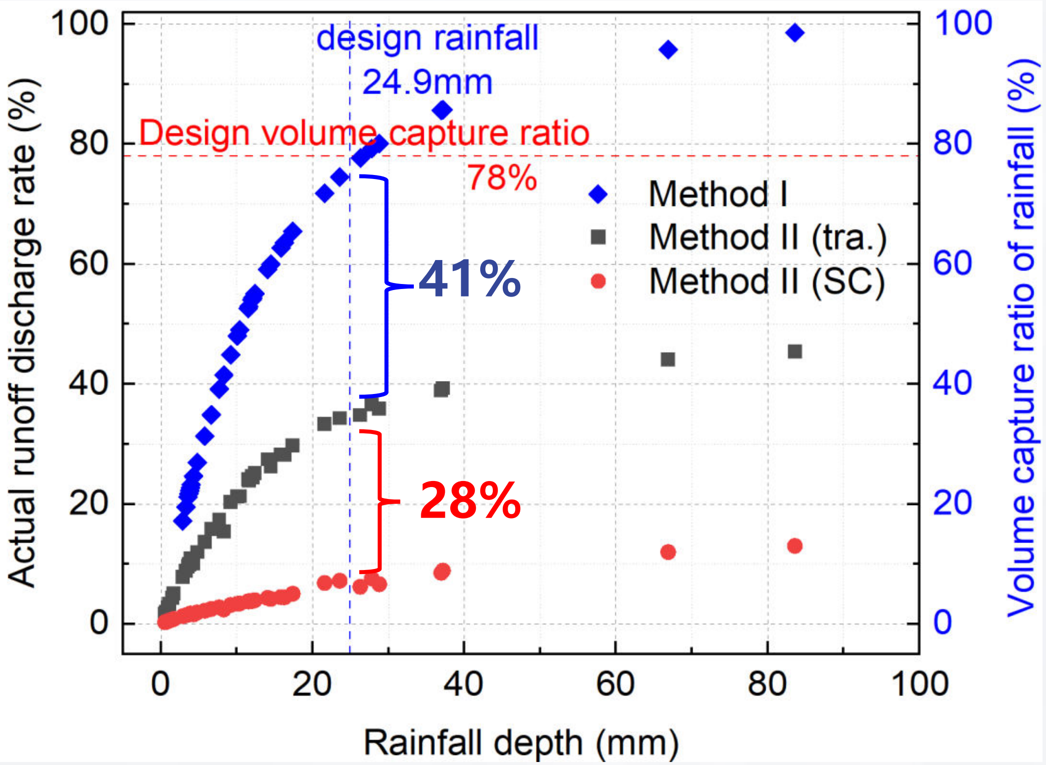
Two method proposed:

- ① When dividing rainfall events, the interval of rainfall events is more than 2 h, and the rainfall depth is higher than 0.5 mm ;
- ② The long-term modeling results are used for statistics, and the outflow volume is sorted according to the corresponding rainfall depth from small to large, volume capture ratio of annual rainfall is calculated by this sorting

3.3 Discussion on volume capture ratio of annual rainfall

Volume capture ratio of rainfall event analysis, DTL drainage basin

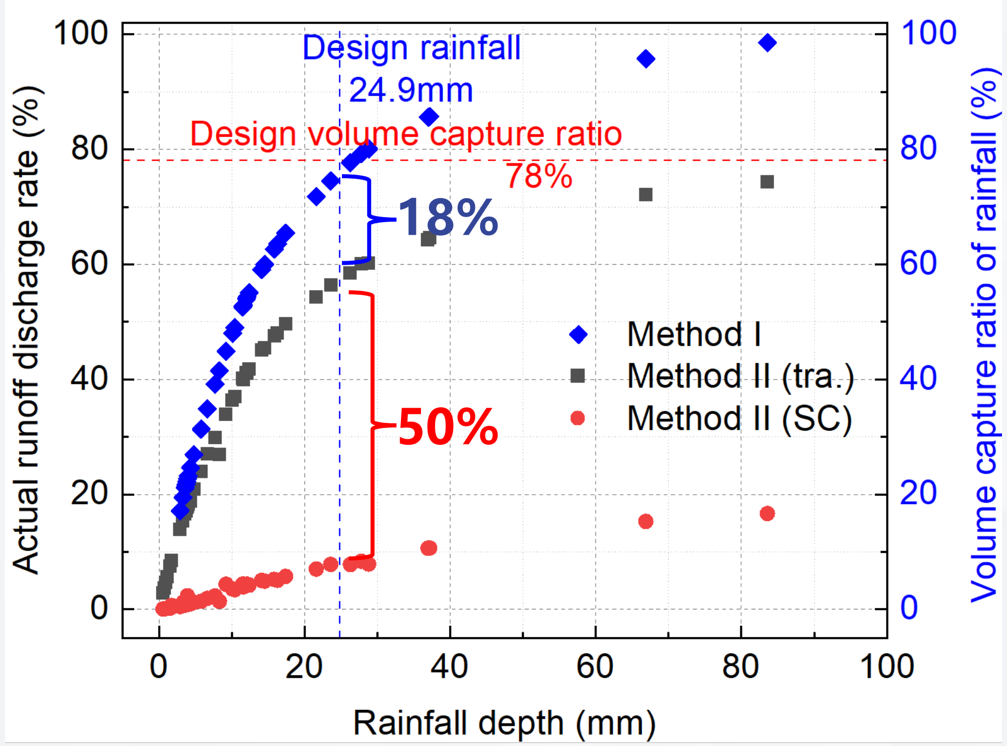
- Volume capture ratio of rainfall event： 78% vs. 24.90 mm
- Method I： 24.90 mm, only 76%
- Method II （tra.） ： 24.90 mm， 35% discharged, 65% controlled
- The difference between Method I and Method II (Tra.): traditional approach has been controlled 41% of volume capture ratio of rainfall event
- The difference between Method II (SC) and Method II (Tra.): sponge city re-development increased 28% of volume capture ratio of rainfall event



3.3 Discussion on volume capture ratio of annual rainfall

Volume capture ratio of rainfall event analysis, XH community

- Volume capture ratio of rainfall event：78% vs. 24.90 mm
- Method I：24.90 mm, only76%
- Method II（tra.）: 24.90 mm，58% discharged, 42% controlled
- The difference between Method I and Method II (Tra.): traditional approach has been controlled 18% of volume capture ratio of rainfall event
- The difference between Method II (SC) and Method II (Tra.): sponge city re-development increased 50% of volume capture ratio of rainfall event



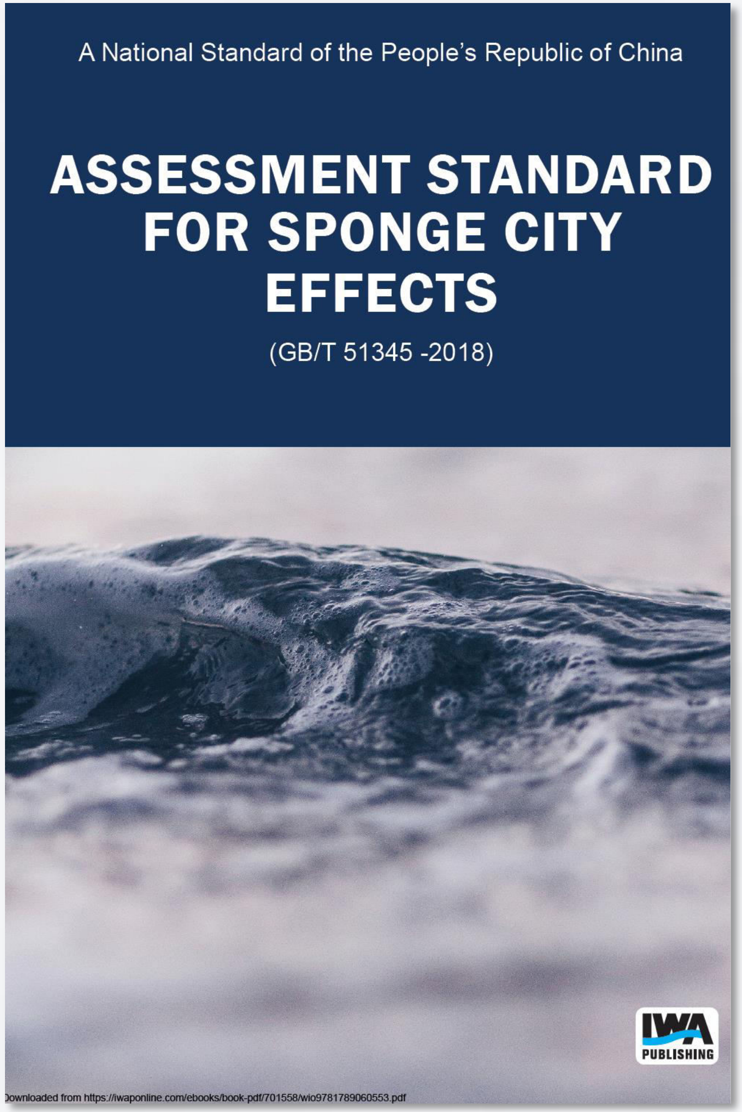
4 Conclusions

– After sponge city redevelopment, the runoff volume was reduced significantly, and runoff appear time and the peak time was also delayed, the flooding risk was obviously reduced, based on 1D/2D coupled modeling and monitoring, whether it's a drainage basin or a community scale.

– Long-term modeling provide a alternative approach to assess volume capture ratio of annual rainfall, it can also assess the pollution control performance combined the water quality monitoring data.

– Considering the randomness characteristics of rainfall events, the relationship between volume capture ratio of annual rainfall and design rainfall depth is considered based on historical data, long-term modeling results based on rainfall data may provide more realistic results.

– The Chinese national standard may provide a reference by urban planners, designers, researchers, investment and management staff in development of modern urban stormwater systems.



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International Water Resources Association (IWRA)

Thank you for your attention!

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