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# "Green structures" for effective rainwater management on roads

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**Abstract**
Rainwater management is one of the important problems of cities. At very strong downpours, storm sewer systems may not capture the rainwater, which floods pavements and roadways. The water flushes fuel and oil traces after vehicles, fallen debris, and other pollutants, which will be moved to the ground, ponds, rivers, seas, etc. In past, the problems were solved using engineering approaches – a set of rainwater receivers, a duct network, and at best, wastewater treatment plants. Now, the sponge city concept is a better solution that uses a biotechnological way for throttling water flows, drainage, and purifying them. The work aims to improve the design of roads to fully absorb rainwater from them with maximum convenience for road users. We propose a design of roads using special "green structures" – rain-garden bands along the sides of roadways. We tested its ability of water capturing on the example of Kyiv city by matching the ability with the strongest precipitation observed. In addition, the proposed plants can extinguish the energy of bouncing cars during road accidents for the protection of pavements.

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## 1. Introduction

Rainwater management is one of the important problems of cities. In past, the main concept of the management is rapid collection of the water by a set of rainwater receivers into city drainage systems, slope water diversion chutes (Vysotsky et al, 2017a; Vysotsky et al, 2017b), etc. The urgent problem of the solution appears at very strong downpours (Senes et al, 2021).

The storm sewer systems may not capture the rainwater, which floods pavements and roadways. The danger of such systems is that the rainwater flushes fuel and oil traces after vehicles, fallen debris, and other pollutants. At strong downpours, water treatment systems cannot treat the large volume. The pollutants are moved to the ground, ponds, rivers, seas, etc.

Now, the sponge city concept is a better solution that uses a biotechnological way for throttling water flows, drainage, and purifying them. We should use a special type of "green structures" – rain gardens – for these tasks. Plants and soil can purify the water, partially absorb it, and transfer it to perforated drainage pipes and the aquifer below them.

This concept is successfully used in many cities of China, the European Union, the United States, etc. Nevertheless, the problems appear on roads in old cities due to

- obsolete drainage systems, which cannot treat large volume of water-flows;
- silted rainwater receivers and ducts;
- obsolete water treatment equipment;
- not enough natural water-absorption areas because of excess building.

In these conditions, a problem of cheap and green water management on roads requires an urgent solution.

## 2. Literature review

The term "sponge city" has been introduced in 2005 by Indian author Van Rooijen but the concept was accepted officially in China in 2013 (Hamidi et al, 2021). China is a leader in the introduction of sponge cities. It has a state Sponge City

Concept program (Xiaoning Li et al, 2016). Detailed analysis of the cities has been performed in (Yixin Zhang, 2021). The authors propose a concept of the design. They perform calculations of design rainwater inflow $V_d$ [m$^3$] and water retention $V_s$ [m$^3$] by different green elements of Suzhou city. The authors didn't provide the height $WRh_B$ [mm] of water that can be absorbed during rain by each sponge facility *i*. This missing information is the most important for calculations of required areas of the corresponding sponge facilities. We assumed that run-off control volume $V_s$ [m$^3$] is the product of area $A_i$ [m$^2$] of the corresponding sponge facility and the sought height $WRh_{Bi}$ [mm]. We calculated the missing information using the least square method (Table 1). The height of water retention is $WRh_B$ = 550 mm.

**Table 1.** Analysis of results of rainwater control study (Yixin Zhang, 2021)

| **Partition** | **Area** | **Designed runoff control volume $V_d$ [m$^3$]** | **Sponge facilities** | | | | **Run-off control volume [m$^3$]** | | **Deviation $V_s$-$V_s'$ [m$^6$]** |
|---|---|---|---|---|---|---|---|---|---|
| | | | Bioretention cell | Permeable pavement | Grassed pitch | Rain garden | By Yixin Zhang (2021) $V_s$ | calculated $V_s' = 10^{-3} \times A_i \times WRh_{Bi}$ | |
| | | | Height of water receiving capacity $WRh_B$ [mm] | | | | | | |
| | | | *550* | *0* | *0* | *550* | | | |
| | | | Sponge Facility Area $A_i$ [m$^2$] | | | | | | |
| **S1** | 5555 | 62.29 | 134 | 619 | 432 | 0 | 73.7 | *73.7* | *0* |
| **S2** | 3900 | 43.73 | 132 | 523 | 302 | 0 | 72.6 | *72.6* | *0* |
| **S3** | 5376 | 60.29 | 183 | 165 | 339 | 0 | 100.65 | *100.65* | *0* |
| **S4** | 5420 | 60.78 | 182 | 344 | 515 | 0 | 100.1 | *100.1* | *0* |
| **S5** | 5818 | 65.24 | 99 | 110 | 351 | 243 | 188.1 | *188.1* | *0* |
| **S6** | 4864 | 54.54 | 150 | 261 | 337 | 0 | 82.5 | *82.5* | *0* |
| **S7** | 9104 | 102.09 | 312 | 495 | 727 | 0 | 171.6 | *171.6* | *0* |
| **S8** | 7650 | 85.79 | 158 | 426 | 701 | 0 | 86.9 | *86.9* | *0* |
| **S9** | 7970 | 89.38 | 172 | 591 | 743 | 0 | 94.6 | *94.6* | *0* |
| **Σ** | 55657 | 624.13 | 1522 | 3534 | 4447 | 243 | 970.75 | *970.75* | *0* |

*Remark: the results of the author's analysis are italicized*

As it is shown in (Fazhi Li, 2021), green structures are very cheap solutions for water management – from 0.7 CNY/(m$^3$·year) or 0.7·0.15 = $0.105 for grassed swales.

In (Jian Wang, 2021) it is proposed to switch from sponge city to sponge watershed concept, which focused on resilience and sustainability. The sponge watershed framework has six modules:

- water resilience;
- water resource;
- water treatment;
- water ecology;
- waterscape;
- water management.

The sponge city concept is very important, but the importance is not enough understood by people (Yunfei Qi, 2021). It requires additional propaganda.

Modern roads are designed for the safety of all road users (Yixin Zhou, 2021). High-speed motor vehicles should be separated from low-speed ones by a green belt or a guardrail. For the safety of pedestrians, pavements should be higher than the roadway. The recommended elevation (Yixin Zhou, 2021) is about 200 mm. In practice, we can observe a much less elevation, which increases the probability of bouncing a car to a pavement during road accidents. In many cities, bicycle bands are parts of pavements, which often make both ways for low-speed vehicles and pedestrians too thick. In all cases, the lowest part of roads is the carriageway, which passes the most of rainwater during strong downpours.

The goal of city design and renovation is city resilience. It's defined by The Resilience Alliance as "the ability of a city or urban system to absorb and absorb external disturbances and maintain the original main features, structure, and key functions" (Weiwei Shao et al, 2021). As it is shown, the downpours are one of the most important disturbances. The problem is getting worse due to global warming (Feng Kong et al, 2021; Jiang et al, 2021), which cause more often and strong precipitations. Together with the rapid urbanization (Feng Kong, 2021; Jiang et al, 2021) and, especially, uncontrolled building, the city flooding events occur too often and require special measures.

As it is shown by the authors, green structures are the biotechnical mechanisms for rising environment-safety of buildings, which can connect technogenic and natural environment in cities. They can solve different problems (Andenæs et al, 2021; Bohan Shao, 2021; Bortolini et al, 2021; Fantozzi et al, 2021; Giacomello et al, 2021; Iffland et al, 2021; Juricic et al, 2021; Kaewpraek et al 2021; Lijiao Liu, 2021; Procaccini et al, 2021; Tkachenko, 2018; Tkachenko et al, 2019a; Tkachenko et al, 2019b; Tkachenko et al, 2020; Tkachenko et al, 2021; Yongjun Pan, 2021) including rising energy efficiency, sanitizing the interiors, exteriors and make them more comfort etc. We consider them as one of the most effective natural solutions for rainwater management, which should be used more widely on different types of city roads. The work aims to improve the design of roads to fully absorb rainwater from them with maximum convenience for road users.

## 3. Introduction of rain-garden bands for taking stormwater from roads

We propose using a special kind of "green structure" – rain-garden bands. There are "green" bands along a road beside its carriageway. The bands are designed to capture the water from both sides. All parts of the road can be at approximately the same level with a slope to the bands. In this case, the bands can have bushes for extinguishing the energy of a bouncing car during a road accident.

The main advantages of the bushes over a bump stop:

- extinguishing the energy of a car without additional bouncing;
- nice appearance;
- $CO_2$ sequestration and oxygen generation.

The disadvantages:

- more space occupied;
- periodical trimming;
- damaging the bushes during road accidents, which require additional maintenance;
- requirements for additional columns with reflective labels for the night traffic.

We propose a green design for different types of roads (Fig. 1, 2) Both sides of each carriageway should be equipped with a rain-garden band. For boulevards, the central green bands should be used as rain gardens. At crossings, the bands should be interrupted by paths. The last one can be elevated for more safety. The elevation should be the same as the pavements at classic roads. In this case, the design should provide enough accessibility for all people.

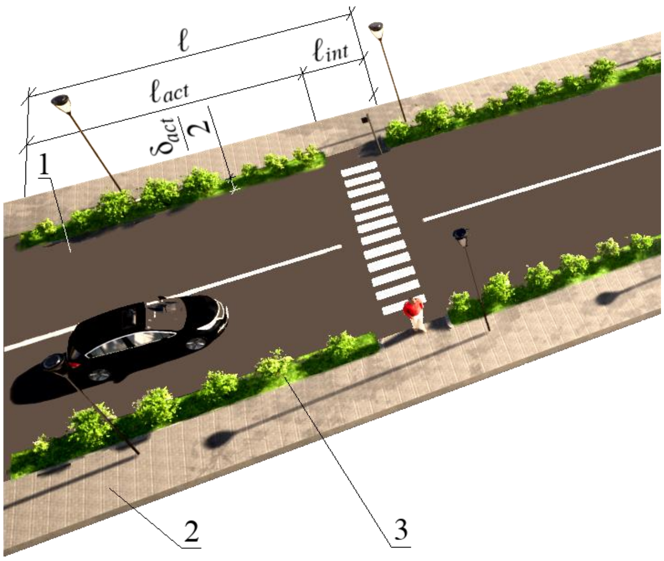


**Fig. 1.** The proposed solution of a street:
1 – carriageway; 2 – pavements; 3 – rain-garden bands


**Fig. 2.** The proposed solution of a highway:
1 – carriageway; 2 – pavements; 3 – rain-garden bands

## 4. Calculation of the rainwater collection ability and engineering measures

### 4.1. Method

The main goal is taking the rainwater for the strongest downpour with high probability. We should calculate the width [m] of the rain-garden bands necessary to capture all rainwater during the strongest possible downpour taking into account the water, fallen to the bands directly. The structure of the bands minimises spreading the water to the ambient soil to avoid erosion and destruction. The first problem is the low validity of long-term climate prognoses due to very strong intervention to natural processes by human activity. Thus, we will use the actual weather observation data.

The calculation should be performed per unit of length (meter). The rain-garden bands should capture all fallen water allowing minimum water flow along the road. The flow should arise only at an interruption in the bands and should be captured before the next interruption. Thus, the interruptions in rain-garden bands should be taken into account using averaged width. If there is (Fig. 1) the length $\ell_{int}$ [m] of the interruptions or length $\ell_{act}$ [m] of the band(s) per the total road length $\ell$ [m] and the actual width of the band(s) is $\delta_{act}$ [m], then the total average width δ [m] can be found by the following equation [m]

$$\delta = \delta_{act}\,\ell_{act} / \ell = \delta_{act}\,(\ell - \ell_{int}) / \ell. \tag{1}$$

If we calculated the required width δ [m], the actual one from the equation (1) [m]

$$\delta_{act} = \delta\,\ell / \ell_{act} = \delta\,\ell / (\ell - \ell_{int}). \tag{2}$$

The maximum rainfall $RFh_{max}$ [mm] can be found from a weather archive or norms.

The width of the main parts of the road should be found from norms. The total width is $b$ [m].

Let us assume waterproof road coverage. The total average width of the rain-garden bands δ for taking all the water can be found from water balance per the unit of the road length [m·mm]

$$\delta\, WRh_B = (b + \delta)\, RFh_{max}. \quad (3)$$

The equation (3) gives the necessary width [m]

$$\delta = b\, RFh_{max} / (WRh_B - RFh_{max}). \quad (4)$$

The physical meaning of the denominator in equation (4) is the actual water collection ability of the rain-garden band. It is less than *WRB* because some part of the height of water retention should capture the rainwater fallen on its surface directly. If there are interruptions, the actual width $\delta_{act}$ [m] should be calculated by equation (2).

The total width of the road with the rain-garden bands [m]

$$B = b + \delta_{act}. \quad (5)$$

Now we should check the possibility of placing the bands. If the road can be expanded by $\delta_{act}$ [m], we will accept the width. If not, the maximum width $\delta_{max}$ [m] should be accepted: $\delta_{act} = \delta_{max}$ [m]. If interruptions, the average width δ [m] should be calculated by the equation (1). Non-captured water *NC* [$m^3$/m] can be found from the water balance per the unit of the road length [m·mm]

$$\delta\, WRh_B + 10^3\, NC = (b + \delta)\, RFh_{max}. \quad (6)$$

After transformations of equation (5), we can find the non-captured water NC [$m^3$/m]

$$NC = \left((b + \delta)\, RFh_{max} - \delta\, WRh_B\right) \cdot 10^{-3}. \quad (7)$$

The corresponding non-captured water height [mm]

$$NC_h = 1000\, NC / (b + \delta) = RFh_{max} - WRh_B\, (\delta / (b + \delta)). \quad (8)$$

After that, we should take measures for the management of the non-captured water-sponge facilities from table 1 or, as a last resort, a storm sewer system.

Finally, it is necessary to distribute the total width of water-garden bands proportionally to the width of the road parts, from which the bands capture water.

### 4.2. Example

Let us consider a road in Kyiv (Ukraine) in fig. 1. Its width with pavements is $b$ = 12 m. Each $\ell$ = 200 m, there is a crossing of 6 m. The rain-garden bands have interruptions of length $\ell_{int}$ = 6.5 m.

The weather archive (Weather, 2021) of Zhuliany airport in Kyiv (Ukraine) says that the maximum rainfall since 01 June 2005 is *RFh* = 53 mm. By equation (4) the average total width of rain-garden bands

$$\delta = b\, RFh_{max} / (WRh_B - RFh_{max}) = 12 \cdot 53 / (550 - 53) = 1.28 \text{ m}.$$

The actual one by equation (2)

$$\delta_{act} = 1.28 \cdot 200 / (200 - 6.5) = 1.33 \text{ m}.$$

The total width of the road with the rain-garden bands by equation (5)

$$B = b + \delta_{act} = 12 + 1.33 = 13.33 \text{ m}.$$

The increase of road width is $100 \cdot 1.333/12 = 11.11\%$.

The width is acceptable. We should distribute the width equally because of the symmetry. Each band will have the width 1.28/2 = 0,64 m. The width will be rounded to 0.65 m.

This result can be used for places with approximately the same maximum precipitation. If the maximum precipitation is less, the width should be decreased below 10%.

## 5. Summary and conclusion

Literature analysis shows that there is an acute problem of flooding cities. The most natural and cheap solution is the sponge city concept. For roads, we propose introducing the special type of "green structures" – rain-garden bands – at both sides of each road carriageway. They are the biotechnical measure for water capturing, cleaning, traffic safety, decoration etc. We propose a method that allows calculation of the width of the bands and estimating non-captured water amount in case of constrained conditions. The method is based on matching the water capturing ability and the strongest precipitation observed. The calculation results show that in Kyiv conditions, the width of roads should be enlarged only by 11.11%. This is acceptable in most cases. Therefore, the improved design of roads solves the task of capturing the rainwater. Future laboratory researches will focus on the actual water capturing and filtering ability of the bands. The damages after flooding are very high comparing to the cost of preventive measures. Thus, in this study, we did not calculate the additional costs of the road. This will be performed at the final stage.

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# 有效管理道路雨水的“绿色结构”

**關鍵詞**
洪水
雨水花园
雨水管理
废水处理
海绵城市

**摘要**
雨水管理是城市的重要问题之一。在非常强烈的倾盆大雨中，雨水管系统可能无法收集雨水，雨水会淹没人行道和道路。水冲走车辆、坠落的杂物等污染物后留下的燃油和油迹，这些污染物将被转移到地面、池塘、河流、海洋等。过去，这些问题都是通过工程方法解决的——一套雨水接收器，管道网络，最好是废水处理厂。现在，海绵城市概念是一种更好的解决方案，它使用生物技术方式对水流进行节流、排水和净化。这项工作旨在改善道路的设计，以充分吸收雨水，为道路使用者提供最大的便利。我们提出了一种使用特殊“绿色结构”的道路设计——沿道路两侧的雨水花园带。我们通过将能力与观测到的最强降水相匹配，以基辅市为例测试了其捕水能力。此外，拟议的植物可以熄灭