Territorial physical and mathematical model of stormwater management

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Abstract. Climate change reduction and adaptation policies are being implemented worldwide through stormwater management in urban areas. Rational use of stormwater could influence the decrease of the "heat island" effect and "cool down" cities. The authors plan to analyze the features of green spaces in the city and demonstrate by a concrete example the opportunity to implement elements of green infrastructure. For widespread use in urban areas, the authors created physical and mathematical model of the territory and recommend variants with four main types of green structures: soil, biotope, shrub, tree. The authors' research proves that with correct analysis of the terrain from the point of view of urban planning, engineering and landscape, with responsible selection of plants of local flora, bio-drainage systems can work well even in regions with a cold climate, such as Russia.

Keywords: green infrastructure, mechanical infrastructure, biofiltration slope, biodrenage ditch, hybrid rain garden, permeable coatings, stormwater management.

1 Introduction

Green spaces have always played an important role in the streets, but before they were used only to create an aesthetic environment. Now green infrastructure is considered as a factor of ensuring sustainable development of the city [1] with its own functions.

The obvious function of green areas in urban spaces is protection against overheating by sunlight [2] and regulation the temperature of the city environment [3]. Creating a protective buffer zone of plants from the traffic flow, we activate the protection for pedestrian traffic. Moreover, such green lanes will protect from excessive noise [4], help to navigate in the city and indicate the direction of movement for walkers. An additional plus will be giving to modern buildings an understandable human scale with an increase in the identity of the place [5].

Harmonious vegetation improves the tourist and recreational infrastructure of the city, increases the cost of land [6]. The results of the study by Federico Dell'Anna, Marina Bravi,
Marta Bottero showed a positive effect on the values of proximity to natural green areas, as well as to regional, urban parks and small natural areas [7]. And long-term use of green spaces reduces the expense of planting new plants.

A large number of green spaces in the city are necessary to perform ecological functions, for example, to reduce the intake of dust and gases, improve water quality and microclimate in general [8]. Green infrastructure helps mitigate landscape fragmentation and improve biodiversity [9]. Green areas retain stormwater, take additional runoff from impermeable surfaces and exchange all the resulting water for carbon dioxide from the air [10]. The bio-drainage benefits of plants decrease the risk of major floods and local flooding through soil filtration of diverted stormwater and precipitation [11].

The international experience of advanced countries shows that the urban planning sphere accumulates geographical, technological, social and political processes, thereby allowing for a synergetic effect from the interaction of these spheres. This has the most favorable effect on the sustainable development of the urban environment and rational use of natural resources [12]. However, the sustainable development of urban areas is under risk due to the effects of climate change.

The World Meteorological Organization predicts an increase of precipitation to almost 50% for the period 2020 - 2026. According to scientists [13], when warming up 1 degree Celsius, the moisture content in the atmosphere increases by 7%. Thus, excess thermal energy is conserved in clouds. Climate change has led to a significant rise in intense slow-moving rainstorms.

Every year, not only the volume of stormwater in cities increases, but also the percentage of sealing of the territory. Covering the land with opaque asphalt concrete materials for the construction of housing, roads, industrial and other objects is the main cause for the degradation of urban soils and increases the workload of storm sewers. The percentage of sealed territories in major cities of the world exceeds 60%, while in the central regions the proportion of such territories increases to 95%.

With an expand in the proportion of solid surfaces, the area of land potentially suitable for landscaping decreases. Which, in turn, caused the formation of thermal anomalies and declined the comfort of the urban environment. Encapsulated soils are having altered air, water and thermal regimes, and violate the boundaries of ecosystems [14]. In addition, impermeable surfaces of transport system serve as an effective transport system for the infiltration of runoff pollutants. A high proportion of such territories threatens urban biodiversity, increases the risk of flooding, and contributes to heating of urban areas.

Despite a large number of studies in this area, there are no significant changes in the adaptation of the urban environment to heavy rains and heat in Russia. Existing natural and green areas in urban conditions have a smaller area compared to the built-up area. When carrying out landscaping in Russian cities, elements of green infrastructure and open drainage are not used, because this is not envisaged in normative documents of any level [15]. The anomalous heat in recent years has negatively affected the heaviness of the course of the coronavirus disease, its consequences, and has led to an exacerbation, first of all, of morbidities of the cardiovascular system [16]. Therefore, the theme of sustainable nature in the city, regardless of climatic risks with a new socio-cultural scenario within walking distance from housing, remains as topical as ever. And the management of urbanization is achieved at the present stage of the development of world urban planning science and practice through the use of new opportunities in the engineering preparation of the urban area. It also includes open drainage systems for maintaining different types of green spaces [17].
In reaction to this problem, our research suggests implementing "green" technologies by the method of minimal impact on the environment in the entire life chain of the city, in order to solve the problems of sustainable development of modern and future society. Thus, we will form a research hypothesis: in the urban environment, through the reconstruction of different types engineering communications for stormwater management, we will determine quantitative indicators for plants in sustainable gardening.

The authors plan to analyze the functions of green spaces in the city and demonstrate by a specific example the possibility of implementing elements of green infrastructure. And also to note the potential benefits of territorial physical and mathematical modeling of the processes with similar solutions in our cities. Thus, the need to determine the vector of development of the "green infrastructure", its role and place as a management system of green areas, determined the importance of the topic of this article.

2 Materials

The authors plan to extend the results of the study to the territories of cities:

- With a humid continental climate;
- With an overloaded storm water drainage system;
- With built-up poorly landscaped and built-up green landscape areas.

Due to significant temperature fluctuations between winter and summer months, as well as differences in the amount of precipitation in summer, Moscow is considered a continental climate zone. Moscow has warm or even hot summers and long cold winters. Humidity is high all year round, although in the spring months it is the lowest. Monthly precipitation varies minimally throughout the year. Most of the precipitation in Moscow falls in the form of rain, but in the winter months almost all precipitation falls in the form of snow, forming a solid snow cover.

The summer of 2020 in Moscow turned out to be the rainiest in the last five years. According to the results of the analysis of flooding and water accumulation carried out in recent years in Moscow, a list of 119 priority problem addresses was established. These are mainly plots on the street and road network, to a lesser extent - yard territories [18]. Most often, the causes of water accumulation are connected with the lack of a drainage network or insufficient capacity of the existing ones.

To solve this problem, the Moscow government has been modernizing the drainage infrastructure for years. In 2021, 33.2 kilometers of drainage networks were updated. Sanitation, a trenchless method of repairing pipelines, has become the predominant type of overhaul of the drainage network. As a result, the depreciation of collector networks decreased by eight percent — from 25% to 17%. Thus, the number of problematic places for water accumulation in Moscow has decreased to 43 addresses in 2022.

One of these remaining problematic addresses is the intersection of Leninsky Prospekt with Lobachevsky and Obruchev Streets (fig. 1).

In the summer of 2021, improvement was carried out in Moscow on part of Leninsky Prospekt. However, the changes did not affect engineering communications and additional parking spaces for cars, due to which stormwater is managed in world urban planning practice. It was the condition that became fundamental for choosing a place to conduct research.

The territory of the probed crossroad belongs to the type of territories with a low building density. According to the terrain map, the intersection is located at the lowest points of the landscape, which means frequent accumulation of storm flows on the roadway,
because the existing elements of the grey infrastructure cannot cope with the load. Also this territory is located in the zone of periodic flooding by groundwater.

Based on the photo fixation, a SWOT analysis of the study area was carried out.

![Ecological map-rating of Moscow districts]

**Fig. 1.** Ecological map-rating of Moscow districts. *Source:* compiled by the authors

<table>
<thead>
<tr>
<th><strong>Table 1. SWOT analysis of the probed crossroad</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Positive aspects</strong></td>
</tr>
<tr>
<td><strong>Internal factors</strong></td>
</tr>
<tr>
<td><strong>External factors</strong></td>
</tr>
</tbody>
</table>
3 Methods

In our territorial physical and mathematical model (hereinafter - TPMM), the physical processes occurring in the territory, namely, hydrodynamics and transpiration with their mathematical description and modeling, will be considered.

The planned result of the TPMM implementation is a new territory plan with the introduction of green infrastructure (hereinafter – GI), which is mathematically substantiated. Having the total area of green spaces and impenetrable surfaces, as well as the total amount of stormwater, we will calculate based on the amount of precipitation (m³) absorbed by 1 m³ of soil with a plant, and mathematically distribute the models of GI over the study area.

Next, we will determine the variants of the GI models. Model A is called "soil" and is basic, since there is no vegetation on it at all (fig.2). Model B is called "soil + biotope" and has several variants presented in the diagram [19]. Model C is called "soil + biotope+ bush" with an estimated height of vegetation cover up to 1m (fig.3). Model D is called "soil + biotope + tree" with an estimated height of vegetation cover above 1m. The names of the presented models are the components of the green infrastructure, which intensively conduct water from the surface.

The flow of rainwater into the saturation zone (that is, green spaces) occurs by infiltration. The possibility of stormwater accumulation is based on the ability of the soil to absorb and retain a certain amount of water. Thus, in order to carry out a mathematical calculation, it is necessary to determine the type of anthropogenic soil with properties in the study area. The control section was made in the most common part of the relief of the selected territory. According to morphological features, the type was determined on the site of Leninsky Prospekt in Moscow is anthropogenic soil with the properties of turf-podzolic soil.

Thus, the amount of stormwater absorbed by each variant of the GI model is calculated by the formula:

\[ V_{sw} = (H_{gw} - 0.5 \times H_{cap}) \times K_m \]

where: \( K_m \) is the moisture capacity coefficient, determined by the moisture capacity of the texture class of the soil;
\( H_{gw} \) – the depth of groundwater, determined by the type of soil;
\( H_{cap} \) – the height of the capillary rise of water in the soil, determined by the texture class of the soil;
\( V_{sw} \) is the volume of stormwater that can absorb 1m³ of a certain type of soil.

The sod-podzolic type of soils belongs to the IV textural class – pulverized medium loam. Their moisture capacity coefficient is 0.69±0.02 [20].

The depth of the groundwater is 10 m, as the Samorodinka River passes nearby. The height of the capillary rise of water in the soil of medium loam is 2 m.

Thus, we will calculate the volume of stormwater that can absorb 1 m³ of soil from the control section.

4 Results
In the terrain of the area under consideration, a rain garden with an area of 200 m² naturally developed. In the middle of intersection is periodically flooded area 2100 m². The prospective catchment area is 27 000 m² of impermeable coatings (fig. 4). The diagram also shows the location of the mechanical infrastructure (hereinafter – MI), which takes 20% of stormwater and precipitation.

**Fig. 2.** Variants of the GI models. Model “A”, model “B”. *Source: compiled by the authors*
In the terrain of the area under consideration, a rain garden with an area of 200 m² naturally developed. In the middle of intersection is periodically flooded area 2100 m². The prospective catchment area is 27 000 m² of impermeable coatings (fig. 4). The diagram also shows the location of the mechanical infrastructure (hereinafter – MI), which takes 20% of stormwater and precipitation.

According to the results of a visual inspection of the territory, the rain garden consists of several variants of GI models. Model A is system-forming, because the soil absorbs more water than plants. On this basis, indicators of water absorption by plants are added to all other models, in accordance with their biological characteristics. The results of these calculations are shown in Table 2.

<table>
<thead>
<tr>
<th>Variants of GI models</th>
<th>calculations</th>
<th>result</th>
<th>Square in rain garden</th>
<th>amount of precipitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model A:</td>
<td>(10m – 0,5*2m) *0,69</td>
<td>6,21 m³</td>
<td>0 m²</td>
<td>0 m³</td>
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<tr>
<td>Model B1</td>
<td>6,21 m³ + 0,005m³</td>
<td>6,215 m³</td>
<td>70 m²</td>
<td>435.05 m³</td>
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<td>6,21 m³ + 0,04 m³</td>
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<td>Model B3</td>
<td>6,21 m³ + 0,06 m³</td>
<td>6,27 m³</td>
<td>35 m²</td>
<td>219.45 m³</td>
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<tr>
<td>Model C</td>
<td>6,21 m³ + 0,007 m³ + 0,045 m³</td>
<td>6,26 m³</td>
<td>15 m²</td>
<td>93.9 m³</td>
</tr>
<tr>
<td>Model D</td>
<td>6,21 m³ + 0,04 m³ + 0,25 m³</td>
<td>6,5 m³</td>
<td>30 m²</td>
<td>195 m³</td>
</tr>
</tbody>
</table>

Source: compiled by the authors

In the sum 1255.45 m³ of stormwater can potentially absorb rain garden nearby Leninskiy Prospekt. However, there is actually much less precipitation. The average precipitation in the summer months is shown in Table 3. The amount of precipitation falling on the territory of the rain garden is insignificant, and even a strong storm in 2020 did not cause flooding in its area. But the Leninsky Prospekt, Lobachevsky and Obruchev streets were flooded because of the impermeable asphalt. In a prospective version, the authors propose to use the absorbing potential of the rain garden and redirect stormwater from hard surfaces to green surfaces.

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Table 3. Calculation of the requirement area of a rain garden
Water catchment area is 27000 m$^2$

<table>
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<tr>
<th>type of rain</th>
<th>ordinary rain</th>
<th>heavy rain</th>
<th>storm in June 2020</th>
</tr>
</thead>
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<tr>
<td>precipitation</td>
<td>5 mm/m$^2$</td>
<td>20 mm/m$^2$</td>
<td>60 mm/m$^2$</td>
</tr>
<tr>
<td>Volume of precipitation</td>
<td>135 m$^3$</td>
<td>540 m$^3$</td>
<td>1620 m$^3$</td>
</tr>
</tbody>
</table>

- 40% of precipitation volume for evaporation

| Volume of stormwater | 81 m$^3$ | 324 m$^3$ | 972 m$^3$        |

-20% of stormwater volume on mechanical infrastructure

| Volume of stormwater | 64.8 m$^3$ | 259.2 m$^3$ | 777.6 m$^3$        |

There is 7.5 m$^3$ (on average) of water per 1 m$^2$ of rain garden

| the area of a rain garden | 8,64 m$^2$ | 34,56 m$^2$ | 103,68 m$^2$        |

Source: compiled by the authors

Thus, a naturally formed rain garden with an area of 200 m$^2$ will easily absorb and retain stormwater from the entire prospective catchment area. But it is irrational to divert all the water into one rain garden, therefore, in a prospective version of the development of the territory, we will add other functional elements of the GI (fig. 5).

Fig. 4. Scheme of the intersection under study. Source: compiled by the authors
Water catchment area is 27000 m²

- Ordinary rain
  - 5 mm/m²
  - Volume of precipitation: 135 m³
  - 40% of precipitation volume for evaporation
  - Volume of stormwater: 81 m³
  - 20% of stormwater volume on mechanical infrastructure

- Heavy rain
  - 20 mm/m²
  - Volume of precipitation: 540 m³
  - Volume of stormwater: 324 m³

- Storm in June 2020
  - 60 mm/m²
  - Volume of precipitation: 1620 m³
  - Volume of stormwater: 972 m³

There is 7.5 m³ (on average) of water per 1 m² of rain garden

The area of a rain garden
- 8.64 m²
  - Volume of stormwater: 64.8 m³
- 34.56 m²
  - Volume of stormwater: 259.2 m³
- 103.68 m²
  - Volume of stormwater: 777.6 m³

Source: compiled by the authors

Thus, a naturally formed rain garden with an area of 200 m² will easily absorb and retain stormwater from the entire prospective catchment area. But it is irrational to divert all the water into one rain garden, therefore, in a prospective version of the development of the territory, we will add other functional elements of the GI (Fig. 5).

Fig. 4. Scheme of the intersection under study. Source: compiled by the authors

Fig. 5. Prospective scheme of the intersection under study. Source: compiled by the authors.

5 Discussion

A biofiltration slope naturally formed on the right side of Leninsky Prospekt. In order to improve the efficiency of cleaning the storm water from the sidewalks, the authors propose to additionally equip the terracing of this landscaped area. This will also help slow down the flow of stormwater and ensure its forced filtration from large suspensions (particles) on each terrace with the help of appropriate vegetation and the subsequent transition to "gray" water that feeds the landscape.

In the territory under consideration, it is also necessary to equip a biodrenage ditch in the north-western part along Obrucheva Street. This will be a barrier for storm water to enter the roadway and the flooding area in the middle of the intersection.

Permeable coatings are an important addition to bioremediation technologies. Such paving allows precipitation to pass vertically through solid surfaces, which reduces stormwater runoff, improves water quality by filtering pollutants in the subsurface layers and helps restore the natural hydrological balance in the territory by replenishing groundwater reserves.

Thus, stormwater will be diverted from sidewalks and roadways and absorbed by plants, which will increase their viability and sustainability in the urban environment.

The territorial physical and mathematical model is considered in the author's vision of the application of hybrid models of green infrastructure with appropriate calculations on the capabilities and quantity of collected, transported and accumulated rain and surface water. The territorial physical and mathematical model can actively influence the adjustment of regulatory indicators, and most importantly, the creation of recognizable landscaping with
the inclusion of natural biotopes of different structures and hydrophilicity in order to create a comfortable and stable living environment in Russian cities.

6 Conclusion

In conclusion, it should be noted that to ensure the sustainability of plants in an urban environment help modern technologies such as:

- Installation of a water-permeable coating in pedestrian zones,
- Transverse terracing with natural slowing of the water flow,
- Monitoring of existing infrastructure.

The results of the research demonstrate that the selected research area - the intersection of Leninsky Prospekt and Obruchev Street in Moscow - according to the typology of the transverse profile of the road, reserve areas for green infrastructure and the type of drainage system - is suitable for the introduction of GI elements. Therefore, we will outline the general aspects of integrating green infrastructure into the urban environment:

- compliance of the size of the territory allocated for the GI with the needs of the city;
- the ability to maximize the use of existing vegetation, terrain, water body;
- ensuring the connection of networks of engineering improvement of the territory to urban networks;
- the possibility of building capital structures in the conditions of this relief, soil, groundwater, etc., corresponding to the standards of accessibility of the place;
- territorial reserve of non-architectural space for the possibility of creating areas with retention and accumulation stormwater due to the creation urbanized biotopes in urban areas.

This study has shown ample opportunities for the introduction of "smart" green infrastructure, capable of accumulating large volumes of rainwater in the structure of technological biotope due to modern approaches in the engineering preparation of territories, thereby actively influencing the processes of urbanization, flood control and flooding of urban areas.

References