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Geoecological assessment of the structural stability of a mountain city based on morphological analysis and the CRITIC method

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Abstract. Mountain cities are characterized by high spatial heterogeneity, limited territories suitable for development, and increased vulnerability to anthropogenic impact. The research presents an approach to assessing the spatial structure and environmental sustainability of mountain cities based on an integral index of structural and planning indicators, tested on the example of Vladivostok. The index is formed using indicators characterizing the structure of the city's water-green framework. The structural elements of the green infrastructure were identified by the method of morphological spatial analysis (MSPA), the weights of the indicators were determined by the CRITIC method, taking into account their variability and mutual correlation. The obtained index made it possible to identify a pronounced spatial differentiation of the ecological stability of the territory of Vladivostok, related to the features of the relief, planning structure and functional zoning. The results of the study demonstrate the possibilities of using the proposed approach to identify vulnerable and reserve territories and its application in the zoning of landscaping priorities, the establishment of environmental protection regimes and spatial planning of mountain towns.

Keywords: mountain cities, geoecological assessment, environmental sustainability, green infrastructure, MSPA analysis

Authors' contribution. *V.A. Dmitriev:* ideas; development and design of methodology; implementation of computer code and supporting algorithms; formal analysis; investigation; writing — review & editing; visualization. *D.E. Kucher:* formulation or evolution of overarching research goals and aims; management and coordination responsibility for the research activity planning and execution; supervision. All authors have read and approved the final version of the manuscript.

Conflicts of interest. The authors declare no conflicts of interest.

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Геоэкологическая оценка структурной устойчивости горного города на основе морфологического анализа и метода CRITIC

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Аннотация. Горные города характеризуются высокой пространственной неоднородностью, ограниченностью пригодных для застройки территорий и повышенной уязвимостью к антропогенному воздействию. Авторами представлен подход к оценке пространственной структуры и экологической устойчивости горных городов на основе интегрального индекса структурно-планировочных показателей, апробированный на примере г. Владивосток. Индекс сформирован с использованием показателей, характеризующих структуру водно-зеленого каркаса города. Структурные элементы зеленой инфраструктуры выделены методом морфологического пространственного анализа (MSPA), веса показателей определены методом CRITIC с учетом их вариабельности и взаимной корреляции. Полученный индекс позволил выявить выраженную пространственную дифференциацию экологической устойчивости территории Владивостока, связанную с особенностями рельефа, планировочной структуры и функционального зонирования. Результаты исследования демонстрируют возможности использования предложенного подхода для выявления уязвимых и резервных территорий и его применения при зонировании приоритетов озеленения, установления природоохранных режимов и пространственного планирования горных городов.

Ключевые слова: экологическая устойчивость, зеленая инфраструктура, MSPA-анализ

Вклад авторов. *Дмитриев В.А.:* формулирование идеи; разработка и проектирование методологии исследования; реализация компьютерного кода и вспомогательных алгоритмов; формальный анализ; проведение исследования; создание рукописи и ее редактирование; визуализация. *Кучер Д.Е.:* формулирование исследовательских целей и задач; администрирование проекта; руководство исследованием. Все авторы ознакомлены с окончательной версией статьи и одобрили ее.

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Заявление о доступности данных. Данные, использованные в этом исследовании, могут быть предоставлены автором по обоснованному запросу в связи с существенным объемом.

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Introduction

Mountain cities occupy a special place among urbanized territories, forming in conditions of geomorphological heterogeneity, high degree of fragmentation of the territory and pronounced vertical zoning. In terms of environmental well-being, mountain cities are particularly sensitive to anthropogenic impacts. In a broad sense, settlements that are wholly or substantially situated within mountain areas may be included as mountain towns [1].

In the present study, mountain boundaries are understood as those proposed within the framework of works [2; 3].

Mountain cities are characterized by limited development areas, high cost of relocation, fragmentation, and a high degree of dependence on dangerous geological processes. In these conditions, an analysis of the spatial structure of mountain cities becomes particularly important, allowing us to identify patterns of interaction between relief, development, transport network and natural elements [1].

According to the data used, mountain areas cover 27.6% of the territory of the Russian Federation, within them are 186 settlements classified as urban and there are about 55.1 million people (2024).¹

The present work proposes to consider the result of a study of the spatial structure and environmental sustainability of mountain cities of the Russian Federation on the example of the city of Vladivostok, carried out in the format of the spatial index of structural planning indicators. The Index focuses on identifying and quantifying key elements of a “green” city framework and their integration into the territorial planning structure. Thus, the aim of the study is to develop and test a spatial index of structural indicators of mountain cities.

¹ Population of the Russian Federation by municipal entities. *Official website of Rosstat*. Available from: <https://www.rosstat.gov.ru/compendium/document/13282> (accessed: 26.10.2026).

Materials and methods

Vladivostok — administrative and economic center of the Primorsky Krai and the Dalnevostochny Federal District. The city is located on the Muravyov-Amur peninsula, and the islands of Russky, Popova, etc. are also included in the city. As part of the study, Vladivostok was analyzed within the administrative territory of the city district of Vladivostok, with an area of 757 square kilometers. The territory of the city is varied in topography — there are coastal plains, river floodplains, low and medium mountain ranges.

The green city framework is traditionally seen as the ecological core of a city. Green zones are areas of biodiversity concentration, pollutant deposition, erosion protection [4]. Many researchers view orchards as the nucleus of viable urban animal and plant populations [4–9].

It was proposed to add the “blue” component of the city’s infrastructure to the green zone parameters. The “blue” city framework plays a key role in drainage and drainage, and for mountain cities water bodies are the main source of fresh water, forming the morphological structure of cities [10]. The role of the water body is conditioned by the need to manage not only water resources, but also to reduce the impact of dangerous natural processes such as sediments, floods, reduce the influence of an urban heat island, maintaining biodiversity [11; 12]. Figure 1 shows a diagram of the green infrastructure of Vladivostok.

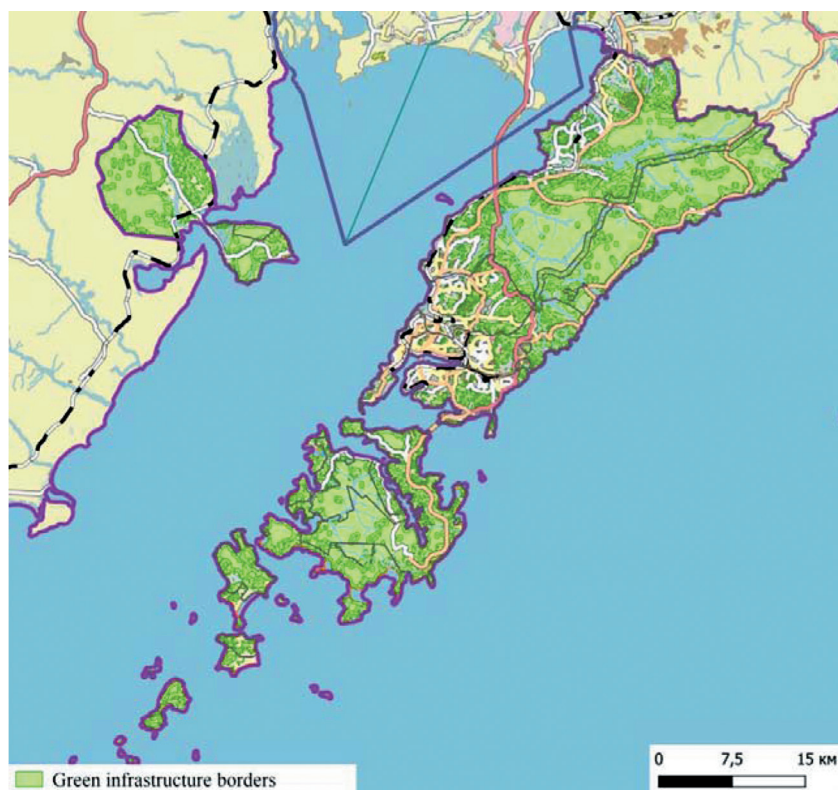


Figure 1. Vladivostok green infrastructure schema

Source: compiled by V.A. Dmitriev.

The calculation of variables was carried out both for the entire territory of Vladivostok and according to the grid. The grid was a collection of squares 1.5×1.5 km, covering exclusively the territory of the administrative borders of Vladivostok. Table 1 provides a summary of the index indicators.

Table 1. Analysing variables

No.	Variable	Measure unit	Description
1.	The share of “isolated” green areas	%	The share of green territories that are not connected by «green corridors» with other objects of the natural complex. The citywide share of «isolated» green areas is 4.13%. The median value of the share on the grid was 7.84%, the median island area was 1.48 ha
2.	The share of “cores”	%	The share of «nuclear» green areas from the total area. The «nuclear» sites occupied a total of 42.1% of the territory of the city of Vladivostok. The median value of the share on the grid was 21.2%, the median area by sector was 17.2 ha
3.	Fragmentation of green areas	units/ha	The number of individual green objects per square kilometer. The median fragmentation value was 2.67 units/ha
4.	Availability of green areas for 1 person within the accessibility criteria	sq.m/person	The number of hectares of green areas per person within walking distance from residential buildings
5.	Occurrence of Red Book species per 1 ha	units/ha	The number of Red Book species recorded within the territory in terms of area
6.	The proportion of closed riverbeds	%	The proportion of riverbeds closed by sewage from the total length of riverbeds within the city
7.	Density of the water network	km/sq.km	Total length of open watercourses per unit area
8.	The proportion of water protection zones that have preserved their natural character	%	The proportion of water protection zones without buildings and artificial turf

Source: compiled by V.A. Dmitriev.

Variables associated with green spaces are based on data [13]. Areas with a krone density of more than 10% were considered “green”, which allowed the separation of random-defined pixels. The total area of Vladivostok within the administrative boundaries is 55.0% green.

Biodiversity related variables were calculated based on observations from users of the open platform iNaturalist.² Parameters associated with water objects were derived from the Open Street Map data. The population by building was calculated

² iNaturalist. Available from: <https://www.inaturalist.org/> (accessed: 26.01.2026).

on the basis of average housing availability of 26.6 square metres of living³ space per person and data on the living area of houses.⁴

The connection of green areas with water objects was assessed on the basis of the intersection of units of green areas — squares, parks and forest massifs with water protection zones rivers and seas. Connectivity was 46.1% on average in the urban area.

The proportion of protected areas that retain nature was estimated on the basis of open data and remote sensing data.

As part of this work, geoinformation modeling methods have been applied, including MSPA analysis, data preprocessing has been carried out, the independence of indicators has been checked, the weights of the investigated variables have been evaluated, and an integral index has been calculated.

MSPA-analysis is a method of spatial analysis based on the mathematical morphology of rasterous data, designed to formalize the classification of green areas into structural elements of the ecological framework (cores, bridges, corridors, branches, edges and insulated spots) to assess the integrity, connectivity and spatial organization of the city's green infrastructure [14]. As part of this work, the MSPA analysis has identified 9 types of green spaces, a detailed description is given in Table 2.

Table 2. **MSPA green infrastructure classes**

No.	Class	Description
1.	Core	The inner parts of relatively large cores
2.	Perforation	Peripheral band around the perimeter of the core
3.	Border Opening	Perforation, a tear in the edge of the core associated with the sealed area
4.	Bridge	An element connecting any two nuclear areas
5.	Edge	Peripheral band around the perimeter of the core
6.	Islet	An isolated fragment
7.	Branch	A partially isolated fragment connected to the edge of the nuclear area
8.	Loop	An element that connects a small area of an uncrowded area to the core
9.	Core-Opening	A small gap in the inner area, revealing the pixels of the green area, surrounded on all sides

Source: compiled by V.A. Dmitriev using [15].

The availability of green areas per person within the accessibility criteria was calculated based on the area of the green facility and its accessibility. Parks and green areas can be divided into the following categories: regional parks, city-wide

³ The volume of commissioned housing in Primorye increased by 7%. *RBC: official website*. Available from: <https://prim.rbc.ru/prim/interview/19/11/2025/691cfe979a794767fc2b1850?ysclid=mnofm8ukyh293640682> (accessed: 26.01.2026).

⁴ Publicly available data. *Territory Development Fund*. Available from: <https://витрина.фрт.рф/opendata?gid=2213474&page=1&pageSize=32> (accessed: 26.01.2026).

parks, regional and federal parks; however, in the present study, regional and federal parks were not distinguished.⁵ Also based on the regional criterion of Moscow⁶ it is permissible to designate the squares as units of green infrastructure, with an area less than a park. Table 3 presents the criteria for selecting different types of green infrastructure and recommendations on their accessibility.

Table 3. Green infrastructure types

No.	Green infrastructure type	Area criteria	Accessibility criteria
1.	Garden	Below 0,5 ha	400 m
2.	A park of regional significance	2 to 10 ha	20 min
3.	A city-wide park	More than 10 ha	45 min

Source: prepared by V.A. Dmitriev using: CR 475.1325800.2020. Code of Rules. Parks. Urban planning and improvement regulations (approved by the Order of the Ministry of Construction of Russia dated 01/22/2020 No. 26/pr). Available from: <https://sro-a.ru/upload/medialibrary/b54/SP-475.1325800.2020.-Svod-pravil.-Parki.-Pravila-gradostroita.pdf?ysclid=mnofpwr05l357199787> (accessed: 26.01.2026); Available from: Order of the Government of Moscow dated 06.08.2002 N 623-PP "On the approval of Norms and Regulations for the Design of Integrated Landscaping in the City of Moscow MGSN 1.02-02". Available from: <https://www.mos.ru/upload/documents/files/4323/623-PP.rtf> (accessed: 26.01.2026).

Thus, the supply of garden was calculated on the basis of creating a mask 400 m around residential buildings, The provision by parks of regional importance was calculated by creating a mask at 20 minutes' walking distance when calculated as the cost of transportation, taking into account the slope of the surface and the average speed of the walk; a park of common urban interest was calculated at 45 minutes' walking distance in a similar way. The overall provision consisted of the total area of accessible squares, parks of regional and citywide importance.

The assessment of biodiversity was based on the calculation of the frequency of occurrence of unique species and unique reddish species per 1 hectare of land area and grid section. The percentage of closed rowers was estimated based on remote sensing data from open sources and data open street map (OSM).

Pre-processing of the data included filling in the gaps when calculating variable shares of tunnelled rivers, area of "isolated" and "nuclear" green zones, density of water bodies, calculation of areas. No emissions and violations detected in the data.

The independence of indicators was assessed based on the calculation of Speerman correlation. The selection of this method is based on the non-parametric

⁵ CR 475.1325800.2020. Code of Rules. Parks. Urban planning and improvement regulations. (approved by the Order of the Ministry of Construction of Russia dated 01/22/2020 No. 26/pr). Available from: <https://sro-a.ru/upload/medialibrary/b54/SP-475.1325800.2020.-Svod-pravil.-Parki.-Pravila-gradostroita.pdf?ysclid=mnofpwr05l357199787> (accessed: 26.01.2026).

⁶ Order of the Government of Moscow dated 06.08.2002 No. 623-PP "On approval of Norms and rules for the design of integrated landscaping in the city of Moscow MGSN 1.02-02". Available from: <https://www.mos.ru/upload/documents/files/4323/623-PP.rtf> (accessed: 26.01.2026).

nature of variables and the absence of preconditions for detecting data distribution normality [16]. Table 4 presents the calculation of the Spirman coefficient for the analyzed data.

Table 4. **Spirman correlation**

No.	Variable	1	2	3	4	5	6	7	8
1	The share of «isolated» green areas	1.00	−0.51	0.76	−0.13	0.20	0.10	0.03	0.41
2	The share of «cores»	−0.51	1.00	−0.34	0.45	−0.03	0.00	0.28	−0.16
3	Fragmentation of green areas	0.76	−0.34	1.00	−0.06	0.17	0.08	0.05	0.35
4	Availability of green areas for 1 person within the accessibility criteria	−0.13	0.45	−0.06	1.00	0.10	0.06	0.25	0.03
5	Occurrence of Red Book species per 1 ha	0.20	−0.03	0.17	0.10	1.00	0.03	0.11	0.13
6	The proportion of closed riverbeds	0.10	0.00	0.08	0.06	0.03	1.00	0.31	0.13
7	Density of the water network	0.03	0.28	0.05	0.25	0.11	0.31	1.00	0.30
8	The proportion of water protection zones that have preserved their natural character	0.41	−0.16	0.35	0.03	0.13	0.13	0.30	1.00

Source: compiled by V.A. Dmitriev.

The analysis of variable independence showed a significant relationship between “isolated” green zones and fragmentation — 0.76, as well as a significant relationship between “isolated” and “nuclear” green zones. Since analytically these indicators are different and allow to estimate not only the absolute value of the area of “isolated” green zones, but also their real distribution in plots — as they can be both relatively large and relatively small, both variables were left in the analysis. In addition, the correlation of indicators was taken into account further in the weighting calculation, potentially reducing the impact of variable dependencies.

The index of structural indicators of water-green infrastructure is based on the sum of normed indicators, divided into positive and negative, adjusted for weight. The overall index formula as follows:

$$I_{\text{cr}} = \sum (X_{\text{norm}} \cdot \alpha), \quad (1)$$

where X_{norm} — variable value normalized; α — weight of variable.

Variable normalization was based on Min-Max normalization. Variable value was based on positive or negative evaluation of the criteria. Thus, the share of tunnelled rivers and fragmented green areas were negative.

The weights of variables were calculated using the Criteria Importance Through InterCriteria Correlation (CRITIC) method, a multi-criteria decision-making method that allows the weight of indicators to be determined based on their variability

and correlation with other attributes [17]. The general formula for calculating the variable weight [17] was:

$$\alpha_j = \frac{std(X_{norm_j}) \cdot \sum (1 - |r_{jk}|)}{\sum_{j=1}^m (std(X_{norm_j}) \cdot \sum (1 - |r_{jk}|))}, \quad (2)$$

where X_{norm} — variable value normalized; r_{jk} — Spirman correlation value.
The weights of variables obtained from calculations are given in Table 5.

Table 5. CRITIC weights

No.	Variable	CRITIC weight
1	The share of “isolated” green areas	0.0811
2	The share of “cores”	0.2051
3	Fragmentation of green areas	0.1163
4	Availability of green areas for 1 person within the accessibility criteria	0.2617
5	Occurrence of Red Book species per 1 ha	0.0493
6	The proportion of closed riverbeds	0.1408
7	Density of the water network	0.1192
8	The proportion of water protection zones that have preserved their natural character	0.0265

Source: compiled by V.A. Dmitriev.

The analysis of variable weights shows that mathematically, the most “strong” variable is green zone endowment, followed by a share of “cores” and a share of closed rows. The least “strong” variables — proportion of water protection zones that retain nature character, occurrence of reddish species, proportion of “isolated” green areas.

Results

As a result of the calculations, an integral index of structural planning indicators within the Vladivostok area was obtained. Figure 2 shows the distribution of index indicators.

The moderately vulnerable class is characterized by a strong differentiation of indicators — the occurrence of high percentages of “isolated” and “nuclear” green zones is roughly equal. There is a fixed increase in the availability of green areas, almost no tunnelled rivers. Index value — from 0.217 to 0.346.

The moderately prosperous class is characterized by a substantial number of nuclear sites and local links, but a differentiated indicator of the endowment of green areas. Tunnelled rivers, “isolated” green zones are rarely found in this class. The class accepts index values from 0.347 to 0.502.

In the analysis, the index was divided into 4 classes according to the Jenks method: vulnerable, moderately vulnerable, moderately prosperous and prosperous. The average for each city was 0.25.

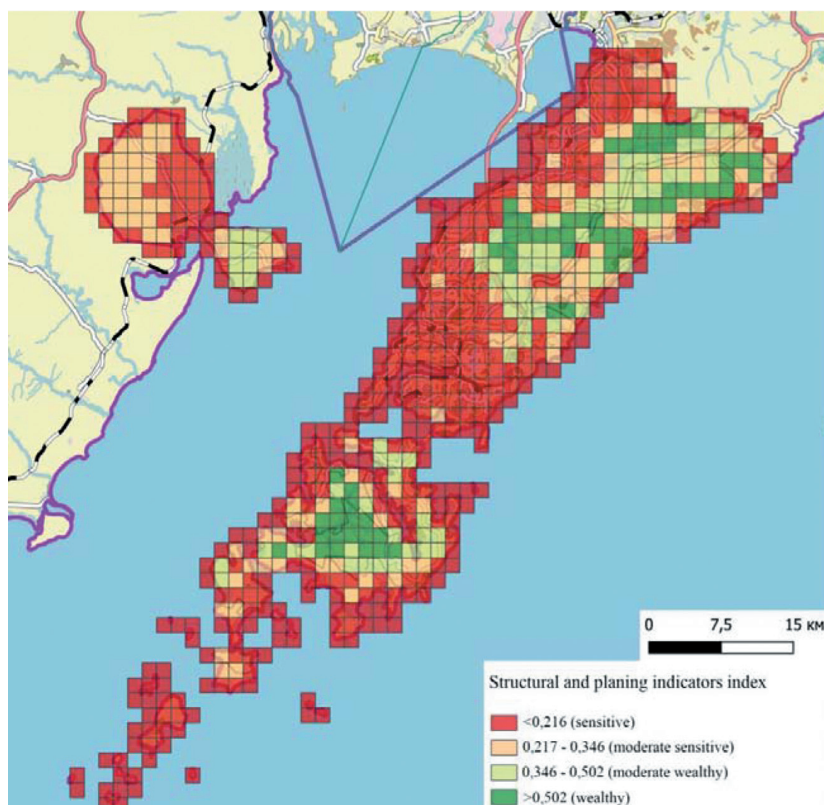


Figure 2. Index categories

Source: compiled by V.A. Dmitriev.

The vulnerable class of the index was characterized by the largest share of “isolated” green areas, the largest number of individual green areas, and the longest shares of tunnelled rivers. Also, this class has the least amount of green space. The index value within the class is less than 0.216.

The prosperous class is the leader in terms of the area of “nuclear” sites, provided with green areas, and stretches of greenery protected zones. It does not have tunnelled rivers, green zones are thinly divided. It accepts values above 0.503.

The spatial distribution of the index has pronounced functional and morphological conditionality. Areas with a vulnerable class are located along the most populous parts of the coast. In terms of morphometric linkage, vulnerable territories are predominantly located on coastal seagrass plains and lower slopes. The prosperous territories are mainly located in the sparsely populated central parts of the peninsula, Russky and Popov. In terms of relief, they are located on the lower incline surfaces and the medium incline surfaces. Table 6 presents comparison of the type of relief and the average value of the index within its limits.

The obtained indicators point to the main pattern of morphological development of the city — a shortage of spaces favorable for construction, forcing use of most available land. In turn, the inconveniences, including slopes and summit surfaces, remain unconstructed.

Table 6. Mean index values

Relief form	Avarage index value
Coastal sea plains	0.198
Lower sloping surfaces	0.321
Medium sloping surfaces	0.360
Low-mountain vertex surfaces	0.313

Source: compiled by V.A. Dmitriev.

Analysis of the differences in the index in the context of linking to the functional zoning of the territory of Vladivostok according to the General Plan⁷ showed that there were no significant differences between the indices within public business and residential areas and those of individual houses. Differences, including the appropriation of the moderately vulnerable, were observed within horticultural farms. The most important role of increasing the index value within residential, mixed and business areas was played by greened slopes, inconveniences, cemeteries.

There is a difference between recreational areas and forest zones. Recreational areas are predominantly associated with moderately favorable areas, while forest areas are associated with favorable ones. These areas may be considered as reserves for further growth of the city.

The analysis of the distribution of 1 quarter of the index showed that the lowest values of the index are concentrated within the central areas of the city — Shkoda peninsula, adjacent parts of the center. Low values were also recorded at the coast, in the area of campus on Russky island.

Conclusion

The developed integrated index of structural indicators of the city gave a quantitative assessment of the sustainability of water-green infrastructure of Vladivostok and showed pronounced spatial heterogeneity. The share of areas with low index values is 61.1%, mainly in densely built-up areas and transport corridors

A list of vulnerable areas and reserve territories has been created to strengthen the ecological framework. Practically these materials are suitable for the adjustment of documents of territorial planning of the settlement. Replicate the approach developed in other mountain towns when calibrating MSPA thresholds and CRITIC weights to local data. Limitations related to errors in the initial layers, selection of binarization thresholds and accessibility parameters, allowing them to be treated as conservative estimates.

⁷ Documents of territorial planning. *Official website of the administration of Vladivostok*. Available from: <https://www.vlc.ru/city-environment/gradostroitelstvo-/architecture-vlc/architecture-general-plan/?ysclid=mnofzazn9f543358669> (accessed: 26.01.2026).

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