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GEOGRAPHY ABROAD

Assessing the Geoecological Functions of the Green Infrastructure in Cities of Canada

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Abstract—An assessment is made of the geoecological functions of the green infrastructure for the cities of Canada by using landscape-basin approach at three spatial levels: regional, intra-urban and local. The study revealed regional and functional differences in the green infrastructure of Vancouver, Toronto and Ottawa, and determined the quantitative relationships between territories that have biospheric, recreational, food-producing and environment-regulation functions. It is shown that the general urban (average according to the spatial scale) level develops many important attributes of configuration of the green infrastructure which come to be intimately linked to the history and modern tendencies of urban development. It is established that for the intra-urban level (Toronto), the large-area elements have the functions of a stabilization of the environment and sustainment of biodiversity, whereas area-limited fragments most often serve as recreational places of the public nearest access. We calculated the proportion of the urban area corresponding to different (according to the functions of runoff formation) types of catchment units; almost one-third of the area is represented by catchment units with no permanent streams or with a transformed drainage system. It is found that the highest percentage of forest land corresponds to the downstream portions of river basins and to areas along valleys, whereas these indicators are much lower in the upstream regions and near drainage divides. It is established that there is almost no correlation between the size of the runoff cell and its percentage of forest land and the degree of development.

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FORMULATION OF THE PROBLEM

Green infrastructure (GI) is a relatively new concept that became the practice of spatial planning at the beginning of the 1990s. In the USA and Canada, GI refers to natural territories and green space performing the functions of runoff regulation and flood control, water and air purification, and support of habitats [1]. In European countries, its components include regions with a high level of biodiversity (including those which form part of the Natura 2000 Networking Programme) within protected areas and their buffer zones, stably functioning ecosystems beyond protected sites (such as flooded terrains, extensive pastures, coastal zones, and forests). Natural complexes capable of performing the role of ecological corridors (river valleys, forested areas and meadows), rehabilitated habitats (specifically, nesting places and fodder fields), artificial crossings (ecobridges and eco-viaducts for crossing roads), multifunctional zones contributing to priority maintenance of ecosystems, and elements of urban greenery (parks, green walls and roofs, sidewalks and road carpets) [2].

Depending on the level and tradition of spatial planning, for analyzing the composition and assessing the functions of GI the world practice uses different scales: local (a block or a micro-district of the city), district or city (a city or a municipal district), and regional (a large urbanized region, a group of such regions or a country in general) [3]. In the USA and Canada, at the level of separate city districts the composition of GI includes engineering elements which contribute to runoff regulation (storm collectors, green roofs, and permeable sidewalks) [1]. At the regional level in urbanized zones of Europe, the components of GI, along with forests, encapsulate agricultural lands with green fences as the territories of relatively extensive nature management that regulate the microclimate of suburban areas [4, 5].

Attempts to implement the strategy of chargeable nature management led to the fact that the identification of GI has been regarded recently as one of the preparatory stages for a subsequent calculation of ecosystem services [6]. The concept of geoecological function is also substantively associated with them, and it will be used throughout this paper. In accordance with the approaches used in [1–3, 6], such approaches include biodiversity conservation, adaptation to and prevention of climate change, runoff regulation, food security and cultural originality measures, creation of conditions for recreation and rest, and improvement on aesthetic attractiveness of a territory.

The national literature also actively discusses the issues related to optimizing urban planning, including protected territories and green spaces in cities through the use of landscape-geographical approach [7–9]. It is obvious that even specially planned and supported elements of GI do not cease to be included in natural matrices: the landscape and basin structure of a territory. The belonging to the landscape structure determines their nativeness, stability and functions in biodiversity conservation at the species and population levels. The place of a GI element in the basin structure largely determines functional integrity and general resistance of urbanized territories (usually characterized by a high degree of sealing of the surface) relative to unfavorable processes of exogenous geodynamics, including those which are associated with the passage of extreme discharges (freshets and floods). These approaches are also applicable for assessing the geoecological functions of unsealed spaces in the GI paradigm [10].

For the urban level, analysis of the spatial belonging of GI to the elements of the basin and landscape differentiation forms part of the procedure of intra-urban landscape planning aimed at an optimization of the territorial structure of cities. Such a method provides new results and identifies territorial organization problems of GI in the cities where the level of availability of green spaces is sufficiently high and where they are characterized by a good condition. Such cities include, for instance, large cities of Canada considered in this paper. Hence, our intention is to highlight the possibilities of and results from using a polyscale approach in analyzing the geoecological functions of GI.

OBJECT AND METHODS

An assessment of the geoecological functions of GI was made for three spatial levels: regional, intra-urban and local (for separate basins). At the upper scale step, as the operational-territorial unit of investigation, we used the urbanized regions within a radius of 100 km from the center (the size was used according to R.T.T. Forman [11]), generally coinciding with the boundaries of so-called metropolitan areas of the cities. Our selection of Vancouver, Ottawa and Toronto was determined primarily by their geographical location, the difference in natural-zonal conditions, and by the built-up urban fabric.

As the maritime city, we used Vancouver, a major Pacific port of Canada (with the area within the boundaries of the metropolitan portion measuring 2.87 thou km^2, and the population of 2.5 million people). The official foundation date of the city is considered to be the year 1886, the same year that the first transcontinental train arrived. By that time there had existed on the territory several settlements roughly identical in size, specializing in timber harvesting and trade in furs and fish. Originally, Vancouver was based on the southern coast of English Bay; later, in accordance with the master plan, it extended southward (in the north, a natural obstacle is represented by the Cascade Range); nowadays, it occupies the peninsula in its entirety between Burrard Inlet to the north and the Fraser River to the south. The city has a rectangular layout; its main streets connect the southern coast of English Bay and the lower reaches of the river as well as running parallel to the shoreline and the southern stretch of the river. Since the very beginning of the city until the present the city's economy has been dominated by the port industry; during the first decades of the 20th century, it was also complemented by intense lumbering. Nowadays, these traditional pursuits has incorporated high-tech sectors, such as biotechnology, cinema industry, and others.

Prior to the start of colonization, the vegetation in the Vancouver area was temperate rain conifer forest, with waterlogged territories occupying large areas. As early as 1888, the largest Stanley Park was established; it is situated on the Stanley Park peninsula in English Bay. In 1890, Vancouver's City Council appointed an elected, administration-independent body, the Vancouver Park Board, with the mission of creating GI.

The second selected object is Ottawa (with the area measuring 5.7 thou km^2, and the population of 1.2 thou people); it sits on a gently rolling morainic plain stretching along the right bank of the Ottawa River and the mouth of its tributary, the Rideau River and is comprised of a group of riparian cities. Arbitrarily primary landscapes of the territory refer to the zonal type of temperature moist broad-leaved and mixed forests of the temperate belt. Formally, the date of foundation of the city is considered to be the year 1854 when the Rideau canal was constructed between the Ottawa Rivera and Lake Ontario which, along with the railroad tracks, transformed Ottawa to a large transport hub in this part of the country. Throughout the entire latter half of the 19th century and at the beginning of the 20th century, the city remained a major center of sawmill industry in all Canada. Timber was mainly used in house building so that fires did serious damage. Unlike Vancouver, it was from the very beginning that Ottawa performed the functions of an industrial and railroad hub; therefore, its central part represented a combination of industrial and residential development pressed to the river and intersected by numerous railroad tracks.

The most radical changes in Ottawa's layout that had their implications for the creation of GI occurred in the mid-20th century. In 1950, the Master Plan was approved (it was developed by French architect-planner Jacques Greber; it was then decided to remove from the center the railroad tracks and industrial enterprises (specifically, this applied for the enterprises on LeBreton Flats: nowadays, it is home to a park, and the main railroad station was relocated to the eastern part of the city). It was proposed to organize around Ottawa a "greenbelt" and ban tree cutting. At present the city performs the functions of the capital city, and an important role in its economy is played by high-tech sectors, health care and education.

A variant of location on the lakeside plain is represented by Canada's most populous city, Toronto (with the area measuring 5.9 thou km^2, and the population of 5.58 million people); it stands on the shores of Lake Ontario, in the zone of temperate moist broad-leaved and mixed forests. Founded to serve as a defense outpost on the border with the USA, the city was distinguished primary by a convenient bay that protected vessels against attack. Toronto was granted city status in 1834 and, by the mid-19th century, became North America's largest center for the manufacture of alcohol products. Most industrial enterprises were situated on the territory directly adjacent to the harbor and the lake shore; before the beginning of the 20th century the city occupied only the old lacustrine plain without stretching onto the slopes of the lacustrine-glacial sandy plain. Relatively rapidly, the original rectangular layout assumed the character of sporadic development; it as only bounded by the slopes of the hills and river valleys. Nowadays, Toronto is a major financial center of the country; the main nonferrous metallurgy, chemical and woodwork and timber industry are located outside the city limits.

At the regional level (for urbanized areas), an assessment of the geoecological functions was made according to the territorial structure of land cover [5]. On Google Earth images, visual interpretation identified eight categories of areas: 1) the zone of continuous development, 2) the zone of suburban development, 3) agricultural lands, 4) forests, 5) mosaic pattern of forest/agricultural lands (forest more than 50%), 6) mosaic pattern of agricultural lands/forests (agricultural lands more than 50%), 7) water bodies, and 8) glaciers and snowpatches. For each of them, the priority goals were identified, with some of the categories performing several functions simultaneously.

At the intra-urban level, the object for study was GI within the boundary of Toronto. Its territory shows a clearly pronounced slope toward the coast of Lake Ontario and is drained the most extensive three river systems: the Don, Rouge and Mimico Creek. An inventory of the elements of intra-urban GI was based on geospatial data from the official websites of Toronto and environmental agencies of Canada.

The analysis of the function of formation and regulation of the river runoff was made within the runoff units within the limits of the city and the adjacent portions of the river basins. The units were identified in the Digital Elevation Model [12] by using the tools of ArcMap 10.0. The structure of land use was determined from land cover data from the official website of Toronto [13]. The study identified eight categories of land cover: built-up territories, roads, other sealed surfaces, forests, herbaceous and bushy territories, barren lands, water bodies, and agricultural lands. Information thus obtained was used in calculating and assessing the degree of colonization of the runoff units.

RESULTS AND DISCUSSION

Green infrastructure at the regional level. Vancouver, Toronto and Ottawa are located in different natural-zonal conditions and have a different socioeconomic specialization. Of them, the largest in area and population size is Toronto. Within the metropolitan areas, the cities exhibit a different structure of land cover (Table 1).

The total share of GI in the metropolitan area, calculated as the aggregate percentage of categories, exceeds 90% in the three cities (varying from 97.4% in Ottawa to 93.1% in Toronto), which permits their condition to be characterized as favorable.

The degree of fulfillment of the geoecological functions by the GI elements at this level is closely associated with the area they occupy [5] (Table 2).

The share of GI ensuring biodiversity conservation fluctuates in the three cities from 49.3 to 78.8%, although almost any one of its elements influences the species, population and ecotope diversity.

The gamut of the recreation functions is also associated with the GI composition. This indicator is highest for Vancouver which is also distinguished advantageously by a wide variety of recreation types offered in near accessible places from the city, specifically by the existence of glaciers and perpetual snow attracting people engaged in mountain skiing.

Assessing the degree of representation of GI elements with complex functions is made difficult by relativity of their identification. The three cities considered in this study showed a high share of GI performing the climate-regulating (with respect to a changing global climate) and food functions. However, a monitoring of the effectiveness of their realization is hampered: in the former case, by a shortage of actual assessments of mesoclimate trends in each city's region

Table 1. Land cover structure within a radius of 100 km from the center in cities of Canada, %

Category of land cover	City		
	Toronto	Ottawa	Vancouver
Zone of continuous development	3.3	1.7	2.9
Zone of suburban development	3.6	0.9	1.2
Agricultural lands	14.0	11.9	19.7
Forests	3.9	45.4	35.7
Mosaic pattern of forests/agricultural lands (forests more than 50%)	44.7	–	–
Mosaic pattern of agricultural lands/forests (agricultural lands more than 50%)	0.3	36.1	–
Water bodies	30.2	4.0	34.8
Glaciers and snowpatches	–	–	5.7
Total	100	100	100

Note. Dash – this category is absent.

Table 2. Geoecological functions of green infrastructure in cities of Canada

Geoecological function	Category of land cover (see text)	City		
		Toronto	Ottawa	Vancouver
Biodiversity conservation	4, 5, 7	78.8	9.3	70.5
Mitigation of consequences of climatic changes and adaptation to them	3–6	62.9	93.3	55.4
Regulation of water regime	3–8	93.1	97.4	95.9
Food supply	3, 6	14.3	48	19.7
Conditions for tourism and recreation	4, 7, 8	34.1	49.3	76.2

and, in the latter case, by the complexity of determining the degree of involvement of agricultural lands in food supply precisely to the urban population.

The overall spatial composition of GI in the three cities (configuration of the ecological framework) has characteristic properties associated with the partly inherited landscape structure, layout composition and the history of development. Thus, in Vancouver the composition of intra-urban GI is dominated by cores and separate green fragments (patches) interconnected by “green ways” which provide access to all of the important urban facilities for bicyclists and pedestrians. In this case, the overall configuration of the structure is largely formed by the original, historically inherited layout according to a rectangular grid. The external restrictions on “urban sprawl” here have a natural origin. The mountain ridges beyond the city limits that are occupied by conifer forests were never meant for agricultural or urban development.

The “greenbelt” in Ottawa is included in the city limits; it began to be created in 1956, and to date it separates the historical center from Nepean and Gloucester [14]. The structure of the ecological framework of the metropolitan area includes, along with the belt, the radial green spaces, so-called rural pathways [15]. The agricultural past of the region is inherited in the high proportion of cultivated lands, a characteristic property of GI in Canada’s capital city.

Intra-urban GI in Toronto has a characteristic tree-like structure, because it is mainly formed by ecological corridors along the river valleys, the upper reaches of which beyond the city limit join Toronto’s “greenbelt” (created in 2005) with an area of more than 7300 km^2 [16]. The significance of this buffer zone is increased due to a greater (than in the other two cities) industrial specialization of the suburbs, including in the sectors of nonferrous metallurgy and chemical industry.

Functional characteristics of GI at the urban level (exemplified by Toronto). The area of Toronto within the city limit measures 630 km^2 (nearly by a factor of 10 smaller than the area of the Greater Toronto, the metropolitan area), with 84 km^2 being occupied by urban forests, a critical element of GI (about 13% of the area), and the availability of green space is 3.24 hectares per thousand people [16]. The territory occupied by the city has a complex landscape structure. The sandy lowland plain occupied by the park, port facilities and low-rise buildings is adjacent directly to Lake Ontario. Further to the north there lie the complexes of the lacustrine-glacial sandy plain which is drained by numerous rivers (the Mimico Creek, Humber, Don, Rouge, and others) with clearly pronounced steep-slope valleys, still not built up. The shoreline of Glacial Lake Iroquois formed about 12.5–12 ka and runs via the center of today's Toronto with bluffs as high as 15 m [17]. Apartment buildings, and also the production and other infrastructure are situated to the east of the Don valley and in the northern part of the city, on the surface of sandy morainic plains.

The composition of Toronto's urban forests is dominated by *Acer platanoides*, *A. saccharum* and *A. negundo*); they account for more than 30% of the entire area of leaf surface. The most numerous ten species also include *Fraxinus pennsylvanica*, *Picea glauca*, *Acer saccharinum*), *Ulmus americana*, *Thuja occidentalis*, *Pinus nigra*, and *F. americana*. A dominance of *A. platanoides* (14.9% of the total leaf surface) in the composition of forests is due to the breakout of the Dutch elm disease in the mid-20-th century that destroyed most of trees of this species in North America. In Toronto, many of the dead elm-trees were replaced with *A. Platanoides*; however, this species proved to be highly invasive so that almost no plantations of these elm trees are carried out at present. A total of 116 tree species were recorded in the composition of woody vegetation [18].

From the perspectives of disease resistance and viability of plants in urban forests of North America, the 5–10–20 rule was taken as optimal: not more than 5% of individuals of the same species, not more than 10% of the same genus, and not more than 20% of the same family [18]. According to the quantitative composition of trees, Toronto adheres to this rule with the following exceptions: over 5% of forest correspond to *A. saccharínumn* (10.2%), *A. platanoides* (6.5%), *T. occidentalis* (6.5%), and *F. americana* (15.6%), and much more than 10% correspond to maples (23.8 %) and thujas (17.8%).

A breaking of the rule creates certain threats to forests involving impacts from insects, such as *Anoplophora glabripennis* that was introduced in North America during the 1980s. The vegetation of *A. platanoides* and *A. saccharínumn* enjoys the best condition among the woody species. The vegetation of thuja, elm and *A. sacchainum* is represented by the highest shares of trees in a critical, dying and dead state [18].

Among the species of trees and shrubs used in street green plantations there occur *A. platanoides*, *Gleditsia triacanthos*, *Malus*, *Picea pungens*, *A. saccharinum*, *Syringa*, *Betula papyrifera*, and *Tilia cordata*. More than 55% correspond to invasive species; about 49% of trees of street greenery are in an excellent or good state [18].

GIS analysis of special vector layers revealed the following connections and qualitative relationships between GI elements, their recreation functions and the traditionally identified portions of the ecological framework [8] (Fig. 1).

On the whole, GI of Toronto is formed by a network of large parks (Rouge, Downsview, and Swansea) as well as local parks having the role of patches inside of the city's micro-districts. Some of the parks stretch along the rivers and carry out the functions of ecological corridors connecting the upper reaches of the urban streams with the water-green diameter of the shores of Lake Ontario [19]. These territories are accessible to the public and play a clearly pronounced recreational role. A separate category incorporates bioreserves within the urban limits, namely protected localities with restrictions on access and land use practices [20].

Green infrastructure, and the problems of runoff regulation on urbanized territories. Development and sealing with artificial surfaces radically transforms the functioning of catchment basins. On the one hand, sealing of soil and groundwater depletion disturb the hydraulic connection between the portions of catchment with the river channel and, on the other, asphalt-concrete surfaces are favorable for a faster travel of rain and snowmelt waters to the streams; these factors, however, lead to disappearance of the normal depression-low ground network, to deformation and shoaling of natural channels as well as to a decrease in their discharge capacity. Through feedbacks, the aggregate dystrophy of the catchment-river systems deteriorates the conditions for vegetation growth and alters the entire appearance of the urban landscapes; therefore, the urban landscapes – catchments relationship has a bilateral character. Results of Canadian investigations showed that if the area of forests is increased twice (from 15 to 30%) within the Don basin, then water yield would be decreased by 2.5% for seven months. An increase in the share of impermeable surface by 1%, however, would involve an increase in overland runoff by 2.3% [21].

These processes are particularly important in cities experiencing flood, such as Toronto. In the period between 1959 and 1995, work was done on the prevention of floods, including 15 dams, 12 large canals and two dikes; more than 280 erosion control projects were implemented, including special-purpose work on the creation of green plantations [22].

A geoinformation-based modeling within the city and on the nearest territory identified 76 elementary catchment areas which are categorized into five types: 1) near-watershed regions (sources of rivers, and the runoff formation function); 2) catchment regions of lateral inflows (the functions of runoff concentration

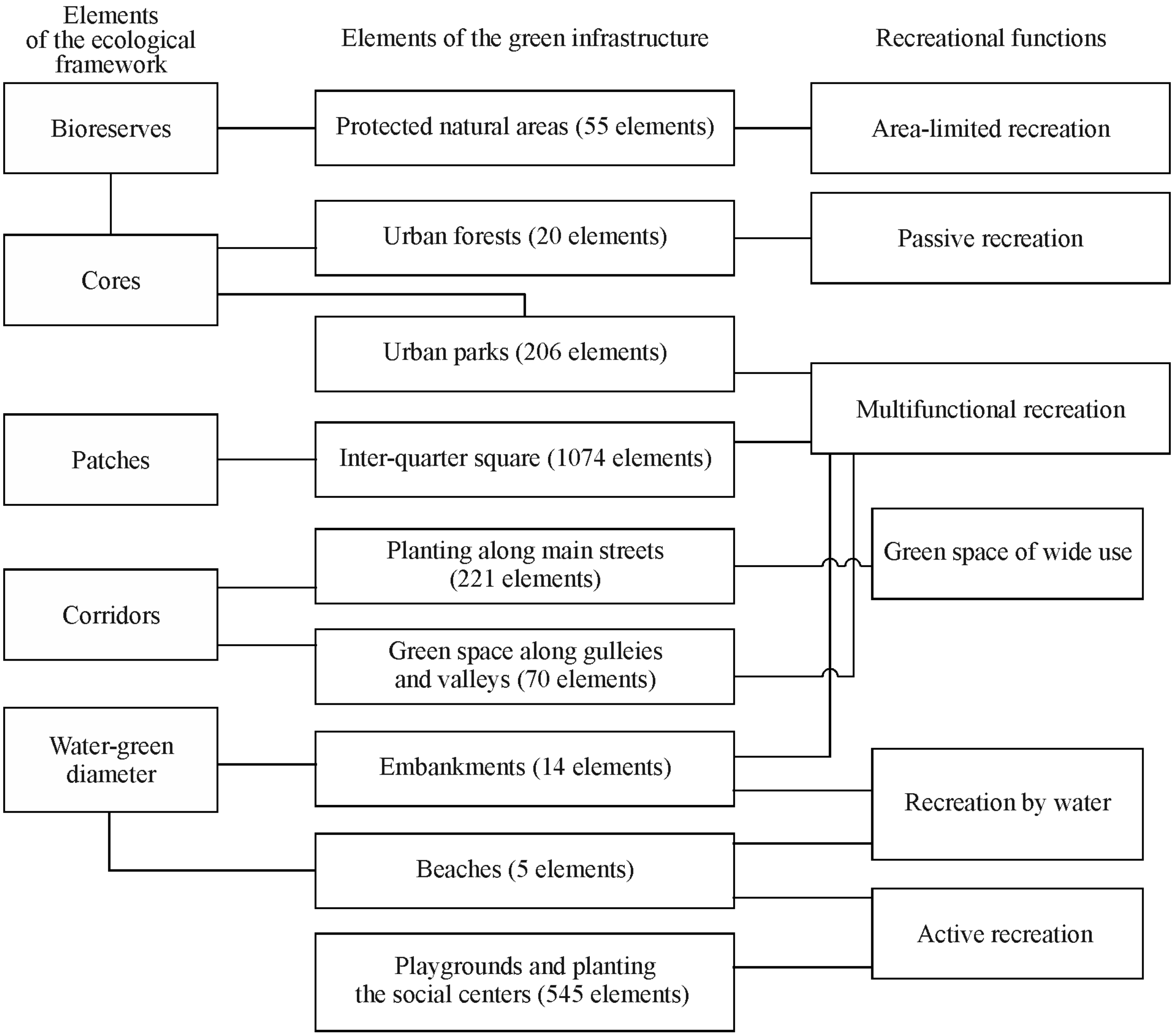

Fig. 1. Schematic map of the elements of the ecological framework in the city of Toronto, and their recreational functions.

and transit, contiguous with summit plains); 3) catchment regions of the estuarine stretches of large rivers (the runoff-receiving function); 4) catchment units with no permanent streams opening directly into the lake (the runoff-conducting function), and 5) catchment regions of the main rivers (transit of the runoff along the main valleys).

The largest area within the city (56%) is occupied by catchment regions of the main rivers (the Don, Rouge, Mimico Creek, and Humber), with the highest percentage of forest land, and with one of the lowest indicators of the degree of development (Fig. 2).

Almost one third of Toronto's territory is occupied by catchment units with no permanent streams or with a transformed drainage system. They occur mostly along the lake's shores. GI is represented not only by woody vegetation but also by lawns, meadows and other herbaceous formations. Their level of colonization is high due to a widespread occurrence of low-rise housing development, asphalt roads and temporal port facilities.

The absolute indicators of forest cover in catchment units vary from 3.4 to 66.8%, and the indicators for the development degree range from 0 to 38% (Fig. 3). The degree of development and the percentage of forest land are generally, only to a small extent, due to the area of the unit. For 70% of the units, irrespective of the size, the percentage of forest land is characteristic within 10–40%, and the degree of development within 10–20%. A clearer correlation is observed between the share of developed and forest territories (Fig. 4). The trend line shows that the larger is the degree of territorial colonization, the lower is the percentage of forest land. The largest-size basins show

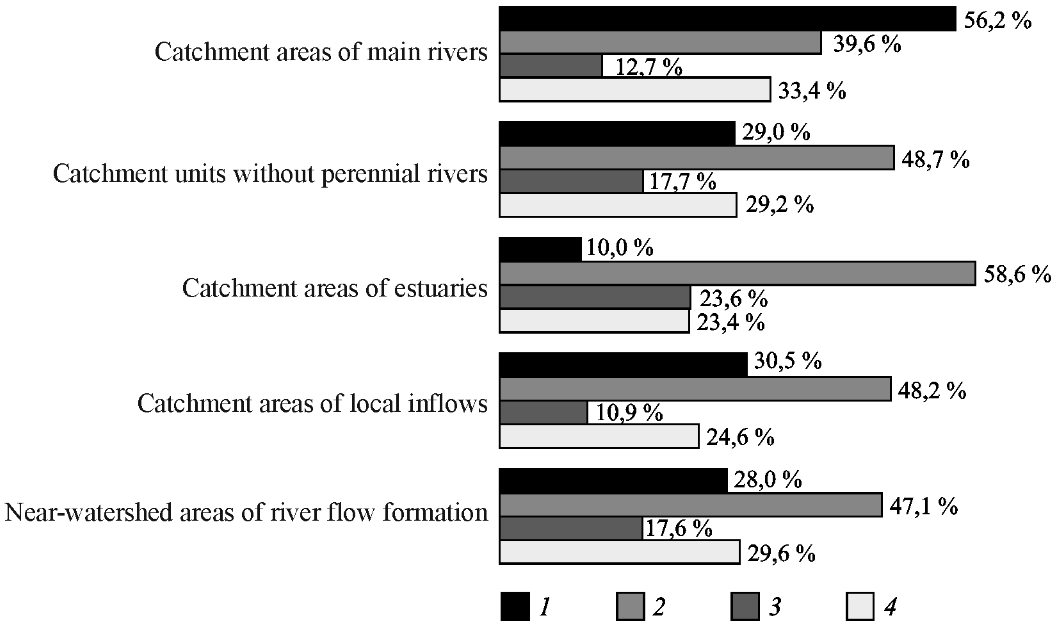

Fig. 2. Quantitative indicators of the main types of catchment units, %.
1 – share in the area of Toronto; *2* – degree of territorial colonization; *3* – degree of development; *4* – percentage of forest land.

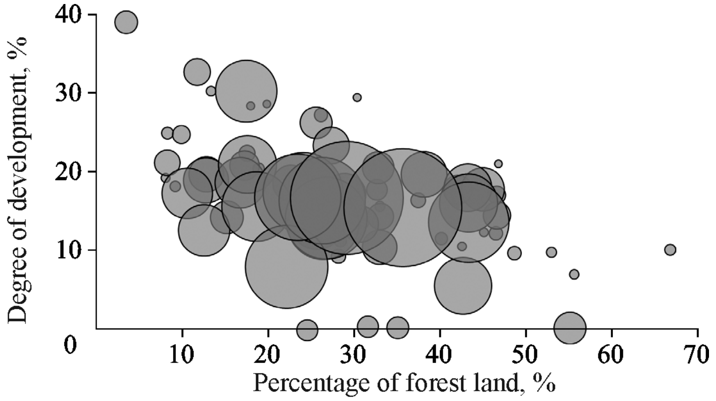

Fig. 3. Degree of development and percentage of forest land of the units differing in size (the size of the circle corresponds to the area of the unit).

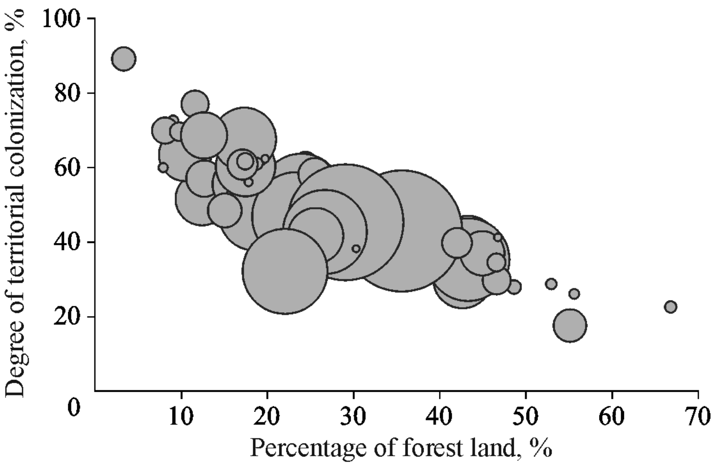

Fig. 4. Degree of territorial colonization and percentage of forest land of the units differing in size (the size of the circle corresponds to the area of the unit).

about the same percentage of forest land (25–35%) as well as the degree of territorial colonization (35–50%). The high indicators of the degree of territorial colonization in many of the basins are associated with the transport infrastructure, but the zones with a high degree of colonization are mainly clustered around the city center.

The natural risks caused by extreme discharges dictate a need to pay special attention to the functioning of the ecological corridors of river valleys [23]. A relevant assessment shows that the basins of large rivers, only in their lower reaches, are well endowed by GI; in their upper reaches and in the regions along watershed divides, however, GI is obviously insufficient. This calls for special (including engineering) measures for increasing surface penetrability.

CONCLUSIONS

The territorial and functional differences as identified at different scale stages of analyzing the geoecological functions confirm the fruitfulness of using an approach of this type. At the level of metropolitan analysis, generally available data on the structure of land cover provide a means of assessing GI from the perspective of regional planning, a balanced territorial structure of the city and the area dependent on it. They help to overcome the terminological differences in determining the boundaries of the urban areas and gain an integral idea of land use practices in the cities within a single country.

The natural structure of the arbitrarily primary landscapes across a territory shows its characteristic features at the upper level, dictating the conditions for greenbelt formation; at the general urban level, producing a mosaic pattern of the largest persisting nature preserves (urban forests, and river valleys connecting them), and at the local level, determining the species composition and territorial structure of urban forest fragments. The recreational functions of GI are distinguished by the greatest uniqueness in each individual city, which is seen from pressure on any one of its components, and from the level of development of small-area patch elements of the nearest generally accessible recreation places.

The result from analyzing the land cover structure at the general urban level implies assessing the spatial composition of the main large elements of GI not only from the perspective of the level of formation of the city's ecological framework but also in terms of the uniformity of the geoecological functions performed by them. In Toronto, the size of the GI components shows a definite association with the goals. Large-area elements have a general environment-stabilizing function as well as a most important function of biodiversity conservation while the area-limited patches most often have the role of the nearest accessible small refugiums and recreation places. Because of the relative character of functional specialization of the different GI elements, the dimensions – function relationship cannot be considered unambiguous.

Despite the good development level of GI in the cities of Canada considered in this study, and the relatively high quantitative indicators, its spatial configuration in each individual case can be improved further, especially within the context of the specific nature of regional ecological problems. The analysis for Toronto showed a particular current importance of optimizing GI in order to appropriately deal with the problem of preserving integrity and functionality of urban catchments.

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