

Blue-Green Factor Mapping in QGIS for Climate-Resilient Urban Water Management

Raghad Awad¹, Štefan Stanko¹, Danka Barloková¹, Ján Ilavský¹, Ivona Škultétyová¹

¹ Department of Sanitary and Environmental Engineering, Faculty of Civil Engineering, Slovak University of Technology in Bratislava, Radlinského 11, 810 05 Bratislava, Slovakia

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ABSTRACT

Rapid urbanisation and climate change continue to increase impervious surface cover in cities, intensifying stormwater runoff, flooding and pollution while reducing natural infiltration. Blue-green infrastructure (BGI) integrates vegetated and water-based elements into urban planning to restore hydrological function and build climate resilience. This study examines the Blue-Green Factor (BGF), an area-weighted indicator of blue-green performance developed in Norway in 2014, situates it within the international lineage of performance-based green area indicators (Berlin's Biotope Area Factor and the Malmö, Stockholm, Helsinki, Seattle and Oslo variants), and evaluates its transition from a spreadsheet-based, property-level tool to a Geographic Information System (GIS)-based workflow in QGIS. The study combines three explicitly separated components: (A) a narrative review of the literature on sustainable urban drainage, nature-based solutions, green area indicators and GIS-based planning; (B) a reproducible demonstration of the BGF-QGIS workflow on the openly documented reference locality of the tool (Ås, Norway), reporting the calculation procedure, the default weighting factors and the interpretation of the resulting score of 0.871; and (C) a document analysis of Bratislava's greenery governance and regulation to assess transferability. The results show that GIS-based BGF mapping improves spatial visualisation, multi-layer data integration and scalability relative to the original approach. A BGF score is a dimensionless weighted ratio that can exceed 1 and is meaningful only relative to thresholds defined within the same scheme (for example, Oslo's residential minimum of 0.7–0.8), while comparative and cost-effectiveness evidence cautions that BGF-type weightings can favour low-cost, lower-performing measures. In Bratislava, the quantity-based green-area coefficient is being complemented by the Ecoindex developed by the Metropolitan Institute of Bratislava, which creates a clear policy niche for BGF-type spatial assessment. The study concludes that BGF-QGIS offers a transparent screening tool for climate-resilient urban water management, provided that weights are locally calibrated, the composition of each score is reported, and the workflow is applied to Bratislava localities in future work.

INTRODUCTION

Rapid urbanization has significantly increased the proportion of impermeable surfaces such as roads, parking areas, rooftops, and pavements in cities. These surfaces prevent rainwater and snowmelt from naturally infiltrating into the soil, resulting in the generation of stormwater runoff. Stormwater runoff is one of the major environmental challenges in urban areas, particularly where effective stormwater management systems, including retention and detention basins, are insufficient or absent. As a result, urban flooding, infrastructure damage, and water pollution have become increasingly common problems in both developed and developing countries.

During rainfall events, runoff collects pollutants deposited through daily human activities on roads, roofs, lawns, industrial zones, and other urban surfaces. The initial phase of runoff, commonly referred to as the “first flush,” often carries highly concentrated pollutants into storm drains and nearby water bodies. These pollutants may include heavy metals, oils, nutrients, sediments, plastics, pesticides, and other contaminants that negatively affect aquatic ecosystems and public health. In many cases, polluted runoff flows directly into streams, rivers, lakes, and oceans without treatment, threatening water quality and ecological stability. Although some pollutants may be reduced before reaching receiving waters, increasing urban activities continue to generate contamination levels that place surface waters at considerable environmental risk [1].

Climate change has further intensified the challenges associated with urban stormwater management. The increasing frequency and

intensity of heavy rainfall events contribute to higher runoff volumes and more frequent urban flooding. Conventional drainage systems are often unable to manage these extreme hydrological conditions effectively. Consequently, cities worldwide are facing growing pressure to develop sustainable and resilient approaches for managing urban water systems while simultaneously improving environmental quality and urban livability [2].

In response to these challenges, blue-green infrastructure has emerged as an important nature-based solution for sustainable urban development. Blue-green infrastructure integrates natural vegetation systems and water management practices into urban planning to improve stormwater control, reduce flooding risks, enhance biodiversity, and support climate resilience. Green components such as parks, green roofs, urban forests, rain gardens, and permeable surfaces are combined with blue elements including rivers, ponds, wetlands, and sustainable drainage systems to create multifunctional urban landscapes. These systems promote infiltration, retention, evapotranspiration, and the natural purification of stormwater runoff, thereby reducing environmental pressures on urban drainage networks and receiving waters [3].

In addition to environmental benefits, blue-green infrastructure provides important social and economic advantages. The integration of natural systems into urban environments contributes to improved air quality, reduced urban heat island effects, enhanced recreational spaces, and increased human well-being. Blue-green infrastructure also supports ecosystem services by strengthening ecological connectivity and protecting urban biodiversity. As cities continue to

expand, the implementation of nature-based solutions has become increasingly important for achieving long-term sustainability goals and improving urban resilience against climate-related risks [4], [5].

The growing importance of blue-green infrastructure has encouraged the development of assessment and planning tools that support sustainable urban design and environmental management. One of these approaches is the Blue-Green Factor (BGF), which is used to evaluate the ecological and hydrological performance of urban areas. The BGF framework assesses factors such as vegetation quality, stormwater management capacity, permeability, and biodiversity potential within urban developments. By quantifying blue-green qualities, the BGF approach supports planners, architects, and decision-makers in integrating sustainability principles into urban planning processes. The BGF was developed in 2014 within the Norwegian Cities of the Future (Framtidens byer) programme by the Planning and Building Agency of the City of Oslo, Bærum Municipality and consultant partners, and was later implemented in QGIS [6], [7].

The Blue-Green Factor belongs to a wider family of performance-based green area indicators that has developed internationally over the past three decades. The earliest and most widely cited example is Berlin's Biotope Area Factor (Biotopflächenfaktor), introduced in 1994 and formally adopted into municipal planning practice in 1997, which established the basic principle of scoring different surface and structure types according to their ecological effectiveness and dividing the resulting sum by the total site area. This approach was subsequently adapted by a number of other European and North American cities under different names, including Malmö's Grönytefaktor, Stockholm's Green Area Factor (Grönytefaktor, GYF), Helsinki's Green Factor, and Seattle's Green Factor, each tailored to local planning regulations, climate conditions, and policy priorities. Oslo's own Blue-Green Factor (Blågrønn Faktor) was developed in 2014 within the national Cities of the Future programme and adopted by the City of Oslo as a municipal norm for residential projects in 2019, building on this lineage, combining prior experience from Berlin and Stockholm with a dedicated pilot project and multi-agency collaboration between planning, environmental, and water and sewage authorities, and is closely linked to Norwegian stormwater-runoff and outdoor-space planning norms. Comparative analysis of these tools shows that although they share a common underlying logic of weighting surface types by their ecological contribution, they differ substantially in complexity, the number and type of categories scored, and their implicit valuation of specific ecosystem services, which has practical implications for how comparable BGF-type scores are across different cities and national contexts [8], [9].

Empirical evaluation of these tools has also identified important limitations that are directly relevant to how BGF-type indicators should be interpreted and applied. A recent cost-effectiveness analysis of Oslo's Blue-Green Factor found that measures with simple vegetation layers, such as lawns and sedum coverings, tend to be the most cost-efficient for developers to install because of their low implementation cost and long service life, whereas structurally more complex measures, such as green walls, intensive green roofs, and rain gardens, deliver substantially greater benefits for air-pollution regulation, runoff reduction, and biodiversity support but at a higher cost. This asymmetry means that, in its current form, the BGF scoring system may inadvertently bias private developers toward low-cost, lower-performing blue-green infrastructure rather than the structurally complex measures that deliver the greatest ecosystem-service returns, and the study accordingly recommends revised weightings and more spatially differentiated performance criteria tailored to local socio-ecological priorities [10]. This finding is an important caveat for any city, including Bratislava, considering the adoption or adaptation of a BGF-type instrument: a high aggregate BGF score does not necessarily indicate that the most effective blue-green measures, from a hydrological or ecological standpoint, have been selected.

Climate change adds a further layer of complexity to the design and interpretation of blue-green infrastructure assessment tools. Conventional stormwater design has historically relied on the assumption that extreme-rainfall statistics are stationary over time, an assumption that is increasingly being challenged: analyses combining extreme-value statistics with Bayesian inference have shown that treating historical rainfall records as stationary can substantially underestimate the intensity of future extreme-precipitation events, with direct consequences for the sizing and expected performance of both grey and blue-green stormwater infrastructure [11]. This body of evidence reinforces the argument that blue-green infrastructure assessment and planning tools, including the BGF, need to be understood as operating within a changing climate baseline rather than a fixed historical one.

Blue-green infrastructure is also commonly situated within the broader international policy concept of nature-based solutions (NbS), defined by the International Union for Conservation of Nature (IUCN) as actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, while simultaneously providing human well-being and biodiversity benefits [12]. Framing blue-green infrastructure and the BGF within this wider NbS discourse is useful because it connects a technical, site-level assessment tool to the broader social-ecological-technological systems in which cities operate, where the benefits derived from green and blue infrastructure depend not only on the biophysical characteristics of individual sites but also on the surrounding institutional, social, and technological context in which they are embedded and maintained [13].

Recent advances in Geographic Information Systems (GIS) and spatial analysis technologies have further improved the application of blue-green assessment methods. GIS-based approaches, including QGIS, enable the mapping, visualization, and analysis of environmental characteristics across larger urban areas. The integration of remote sensing data, GIS datasets, and digital planning tools provides opportunities for more efficient evaluation of blue-green infrastructure performance and supports data-driven urban planning strategies. These technologies contribute to better decision-making processes by identifying areas vulnerable to flooding, insufficient green coverage, and environmental degradation [7], [14].



Figure 1. Stormwater on the road in a village after a heavy rainfall (Source: <https://www.cistavoda.sk/blog/slovaci-bojuju-za-cistu-pitnu-vodu/>)

METHODOLOGY

Research Design

This study combines three components that are reported separately so that the literature-based interpretation can be clearly distinguished from the original analytical work. Component A is a structured narrative (non-systematic) review of the literature on sustainable urban drainage, nature-based solutions, performance-based green area indicators and GIS-based planning (Sections 1,

2.3–2.5 and 3.1). Component B is a documented and reproducible demonstration of the BGF-QGIS mapping workflow, including the derivation and interpretation of a BGF score (Sections 2.6 and 3.2). Component C is a qualitative document analysis of the governance and regulatory context for blue-green infrastructure in Bratislava, used to assess the transferability of the approach (Sections 2.2, 3.3 and 4).

For Component A, sources were selected purposively according to three criteria: (i) direct relevance to BGF-type indicators, to the performance of blue-green infrastructure, or to GIS-based BGF implementation; (ii) publication in peer-reviewed journals or by the public authorities and research institutes responsible for the instruments discussed (municipal norms, national regulations and institutional technical reports); and (iii) preference for primary sources describing the instruments themselves over secondary descriptions. Because the review is narrative rather than systematic, it is intended to establish the conceptual and evidential basis for the analysis rather than to provide an exhaustive quantitative synthesis. Bibliographic details of all cited sources were re-checked during revision.

For Component C, the analysis draws on peer-reviewed research on Bratislava's urban greenery governance [15], the binding part of the city's zoning plan [16], and publicly available information on the Ecoindex developed by the Metropolitan Institute of Bratislava (MIB) and its legal basis [17], [18], [19]. Statements about Bratislava's policy instruments are attributed to these sources and describe the instruments as documented; their effectiveness was not evaluated in this study.

Urban Greenery Governance in Bratislava

Bratislava developed historically from its old town centre and the surrounding villages that were later incorporated into the city, and it is today divided into 17 municipal districts, including Staré Mesto, Petržalka, Ružinov, Karlova Ves, Rača and Nové Mesto. Public greenery is administered on two levels: city-level greenery planning is the responsibility of the Municipal Architect Office, while the districts administer public green areas in their territories, and the maintenance of individual plots is shared between the city and the relevant district [15]. Climate-adaptation objectives for urban greenery were set out in the city's 2014 adaptation strategy and its 2017–2020 action plan, which call for more, better-quality and more accessible green spaces, including street trees, pocket parks, green facades and green roofs, as summarised by Belčáková et al. [15].

In land-use regulation, the binding part of the Bratislava zoning plan controls greenery primarily through the green-area coefficient (koeficient zelene, KZ), defined as the ratio of countable green areas, that is vegetation on natural ground and above underground structures, to the total area of the regulated plot [16]. Because KZ measures the quantity of green area rather than its hydrological or ecological quality, MIB has developed the Ecoindex, a performance-based instrument discussed in Section 4 [17]. This regulatory setting, a quantity-based coefficient in force and a quality-based index being introduced, defines the policy niche that a BGF-type assessment would occupy in Bratislava.

International Precedents for Performance-Based Green Area Indicators

Before examining the Blue-Green Factor and its QGIS-based implementation in detail, it is useful to situate the tool within the broader family of performance-based green area indicators from which it descends. As noted in Section 1, Berlin's Biotope Area Factor established the foundational logic of these tools: a numeric score representing the ratio of ecologically effective surface area to total site area, calculated by assigning differentiated weighting factors to categories of surface and structure, such as sealed pavement, semi-permeable surfaces, vegetated roofs, and vegetation connected to the subsoil.

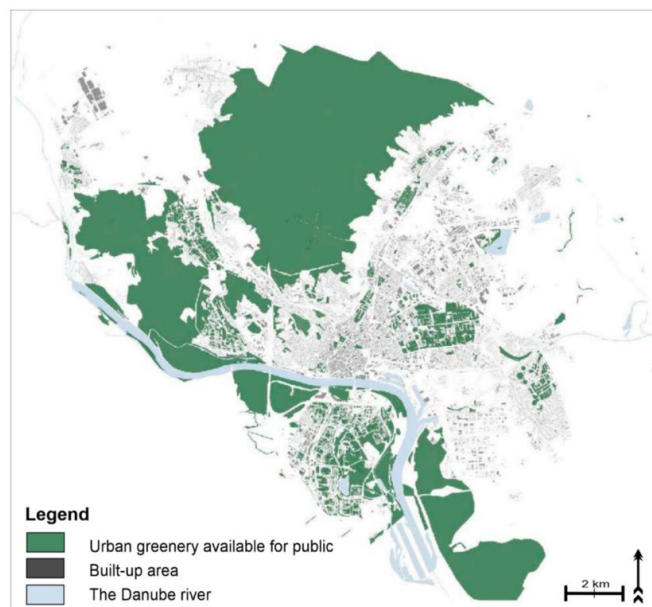


Figure 2. Potential urban greenery areas in Bratislava based on maximum utilisation of available spaces (Source: reproduced from Belčáková et al. [15], Figure 8, under the CC BY 4.0 licence).

This basic architecture was subsequently adapted by Malmö, Stockholm, Helsinki, Seattle, and Oslo, among other cities, each modifying the category list, minimum thresholds, and scoring weights to reflect local climate, regulatory, and planning priorities [8]. A comparative study of three of these instruments -- Berlin's Biotope Area Factor, Stockholm's Green Area Factor, and Oslo's Blue-Green Factor -- found that while all three share the same underlying scoring logic, they vary considerably in structural complexity and in which ecosystem services they implicitly value most heavily, with Oslo's BGF placing particular emphasis on stormwater retention in line with its integration alongside a minimum stormwater run-off requirement and a norm for minimum outdoor residential area [9].

This comparative literature is directly relevant to interpreting the BGF methodology used in the present study, and to any future adaptation of a BGF-type instrument in Bratislava, for two reasons. First, it clarifies that BGF-type scores are not directly comparable across cities unless the underlying category lists and weightings are the same, since a given numeric BGF score in one city's system does not necessarily correspond to the same combination of ecological or hydrological measures in another [8]. Second, it draws attention to a methodological risk identified in economic evaluations of Oslo's BGF: because the tool scores measures primarily by area and category rather than by a full life-cycle cost-effectiveness analysis, it can create an incentive structure that favours low-cost, structurally simple greening measures (such as sedum roofs and mown lawns) over more expensive but hydrologically and ecologically more effective measures (such as rain gardens, intensive green roofs, and engineered wetlands), unless the weighting scheme is deliberately adjusted to counteract this bias [10]. This finding underscores the importance of pairing BGF-type spatial assessment, of the kind demonstrated in Section 2.6, with periodic review of the underlying scoring weights against independent evidence on the hydrological and ecological performance of specific blue-green measures.

Economic valuation studies of urban green infrastructure provide a complementary perspective. A pilot valuation study of Oslo's green infrastructure, combining several value-transfer methods including meta-analysis of willingness-to-pay for green space, hedonic pricing, and time-use valuation of peri-urban forest, demonstrated that the ecosystem services associated with blue-green infrastructure can be expressed in monetary terms sufficient to inform municipal decision-making, even where primary valuation

data for a specific city are not available [20]. Although the present study does not itself undertake an economic valuation of Bratislava's blue-green infrastructure, this literature suggests a natural extension of the QGIS-based BGF approach described below: once blue-green elements have been spatially mapped and scored, the same GIS layers can, in principle, be linked to value-transfer methods to estimate the monetary value of the ecosystem services being planned for or lost.

Blue-Green Factor (BGF) Assessment Framework

The Blue-Green Factor (BGF) is an assessment framework developed to quantify and evaluate ecological and hydrological qualities within urban environments. The methodology supports sustainable urban planning by measuring the proportion and quality of blue and green infrastructure elements within a property or development area. The BGF framework considers factors such as vegetation coverage, permeable surfaces, stormwater retention capacity, biodiversity potential, and other environmental qualities that contribute to urban sustainability and climate resilience.

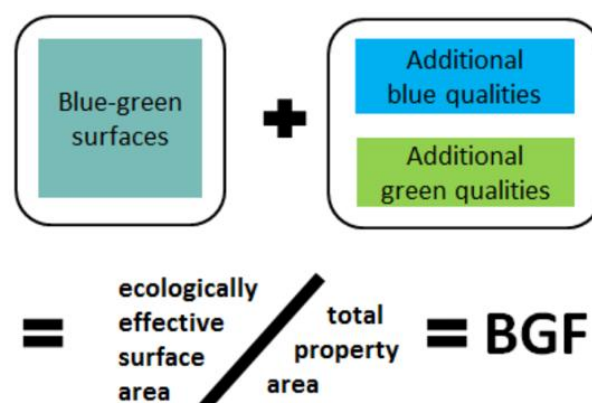
The 2014 BGF Guidance Manual [6] uses a spreadsheet calculator in Microsoft Excel to determine the total blue-green factor of a property. The user enters the areas of blue and green surfaces and of additional ecological qualities, and the BGF score is calculated as an area-weighted sum of surfaces and additional qualities divided by the property area. An Android application, the BGF Calculator developed in the OpenNESS project, subsequently allowed blue-green structures to be digitised on satellite images, but it could not use cadastral boundaries and offered only limited data export [7]. The Excel-based method nevertheless provides a simple approach for evaluating sustainable urban design within individual developments.

Despite its practical contribution, the original Excel-based methodology presents several limitations. Surface areas had to be calculated manually beforehand using field measurements or planning maps prior to entering the data into the spreadsheet. In addition, calculations are usually restricted to one property per spreadsheet, limiting the efficiency of large-scale urban analysis. The methodology also lacks graphical and spatial visualization outputs, reducing its ability to support advanced spatial planning and environmental assessment processes. Consequently, the practical implementation of the Excel-based BGF approach remains limited in broader urban planning applications [7].

These limitations highlight the growing need for more advanced GIS-based approaches capable of integrating spatial datasets, remote sensing information, cadastral boundaries, and urban planning data into comprehensive blue-green infrastructure assessments. As a result, GIS platforms such as QGIS have become increasingly important tools for supporting Blue-Green Factor mapping and sustainable urban environmental analysis.

As discussed in Section 2.3, the way a BGF-type score is weighted has direct consequences for which blue-green measures developers are incentivised to install. In the specific case of Oslo's BGF, cost-effectiveness analysis combining implementation cost, expected lifespan, and expert-weighted ecosystem-service contributions across twelve common blue-green measures found substantial heterogeneity: low-cost vegetation layers scored well on cost-effectiveness despite modest ecosystem-service delivery, while higher-cost, structurally complex measures such as rain gardens and intensive green roofs delivered disproportionately greater benefits for runoff regulation, air-pollution mitigation, and biodiversity support relative to their cost [10]. This is a methodological caution rather than a rejection of the BGF approach: it indicates that a BGF score should ideally be interpreted alongside information on which specific measures contributed to that score, and that municipalities adopting or adapting a BGF-type tool should periodically review category weightings against updated evidence on comparative

measure performance, rather than treating the initial weighting scheme as permanently fixed.



$$\text{BGF} = \text{ecologically effective surface area} / \text{total property area} \quad (1)$$

Schematic of the area-weighted BGF calculation, adapted from Horvath et al. [7]. The operational form of Eq. (1) is given as Eq. (2) in Section 2.6.

Using BGF-QGIS in Urban Planning

The original Blue-Green Factor (BGF) methodology was developed as a planning tool to support the integration of blue and green infrastructure within architectural and landscape design at the individual property level. It enabled municipalities to establish recommendations or minimum requirements for BGF scores that should be achieved within defined plot boundaries. The 2014 BGF guidance further suggested that these minimum thresholds should vary depending on urban density, distinguishing between inner-city and outer-city areas to reflect different environmental conditions and planning priorities. However, assessing minimum BGF requirements at a broader spatial scale, such as neighbourhoods composed of multiple properties with diverse land uses, ownership structures, and landscape characteristics, proved challenging using the original methodology. The limitations of the property-based approach restricted its applicability in larger-scale urban planning and comparative spatial analysis. The integration of BGF into a QGIS environment addresses many of these limitations by enabling cost-effective and spatially explicit mapping of blue-green structures. By combining remote sensing data, GIS datasets, and CAD-based design inputs, the BGF-QGIS approach allows for the analysis of existing and planned blue-green infrastructure across extensive urban areas. This increases the ability to evaluate alternative planning and design scenarios using standardized BGF principles, making the methodology more applicable to strategic urban development and spatial planning processes [7].

Furthermore, the QGIS-based implementation of BGF provides a more robust quantitative assessment framework, aligning ecological and hydrological indicators with other spatial planning datasets. It enables the measurement, comparison, and visualization of blue-green elements in a way that integrates seamlessly with conventional urban planning data. In addition to expanding the spatial scale of analysis, the BGF-QGIS approach improves the visibility of environmental assets that are often undervalued or overlooked in traditional planning practices. Importantly, the methodology is not fixed or universal. Within the QGIS environment, users can adapt the BGF framework by incorporating additional blue-green infrastructure elements and adjusting the weighting of different components within the overall score. This flexibility ensures that the model can be tailored to specific local conditions, planning objectives, and environmental priorities, thereby increasing its relevance and applicability across diverse urban contexts. A prototype urban area is shown in Figure 3, which demonstrates how the digitizing process occurs in QGIS.

QGIS was selected as the spatial platform for this study because it is a free and open-source geographic information system, actively maintained by the Open Source Geospatial Foundation, that supports vector digitising, raster analysis, and integration with external plugins and remote-sensing datasets without licensing cost [14]. This is a practical advantage for municipal planning departments and research institutions with constrained budgets, since it removes the licensing barrier associated with proprietary GIS software while still supporting the polygon-based digitising, attribute scoring, and cartographic output required for BGF mapping. It is worth noting that the BGF-QGIS workflow described here is a static, cadaster-referenced scoring approach rather than a dynamic hydrological or hydraulic simulation model; it does not itself route or time-step simulated rainfall through a drainage network in the way that dedicated stormwater models do. Reviews of stormwater green-infrastructure modelling tools distinguish between this type of static, indicator-based spatial assessment and the dynamic, process-based hydrological-hydraulic models -- such as the U.S. EPA's Storm Water Management Model and comparable platforms -- that are used to simulate runoff volumes, peak flows, and pollutant loads under specific rainfall events [21], [22]. The two approaches are complementary rather than competing: a BGF-type score offers a rapid, spatially explicit, and comparatively low-data way to screen and communicate the blue-green performance of many properties or an entire district, whereas a dynamic hydrological model is better suited to quantifying the expected runoff-reduction or peak-flow-attenuation performance of a specific, already-selected design in physical units. A logical extension of the workflow demonstrated in this study would therefore be to use QGIS-based BGF mapping as a first-pass, district-wide screening tool to identify priority localities, and then apply a dynamic hydrological model to the highest-priority localities identified for more detailed engineering design.



Figure 3. QGIS digitizing of a locality in the BGF-QGIS project environment (Source: Horvath et al. [7], NINA Report 1445)

Demonstration Mapping Exercise: Locality, Workflow and Score Derivation

The mapping demonstration uses the reference locality that is distributed with the BGF-QGIS tool and documented in its user guide: the property of the County Governor in Ås, Norway,

delineated as a single locality (Locality number 1) in the tool's tutorial [7]. This locality was selected deliberately for three reasons.

First, it is a BGF-QGIS application for which the workflow, category definitions, weighting factors and resulting score are all publicly documented, so that each step reported here can be checked by readers against the published documentation and the openly available project files [7]. Second, it is a mixed institutional property containing buildings, sealed and semi-permeable surfaces, lawns, tree canopy and a small open-water element, and therefore exercises most BGF surface categories and additional qualities at the property scale for which the BGF was designed [6]. Third, using an established reference case separates the evaluation of the method from the uncertainties of a first local application. The demonstration locality is not located in Bratislava, and its score is therefore not interpreted as a statement about Bratislava's blue-green performance; applying the workflow to Bratislava localities is the next stage of this research (Section 5).

The workflow follows the documented BGF-QGIS procedure [7] and consists of five steps. (1) The locality boundary is digitised as a polygon in the layer BGF_locality_area, traced along cadastral property boundaries. (2) The entire locality is covered, without gaps or overlaps, by polygons in the layer BGF_flate, each assigned one of the nine blue-green surface types A1–A9 (level BGF1); the 'avoid intersections' snapping option is enabled so that the surfaces partition the locality exactly, because any unmapped area biases the score downwards. (3) Additional qualities B1–E1 (level BGF2) are digitised as separate polygons superimposed on the surfaces, with 'avoid intersections' disabled; tree canopy (C1) is mapped as digitised crown area rather than as a count of trees. (4) Geometries are checked with the QGIS Topology Checker using the rules 'must not have invalid geometries' and 'must not have gaps'. (5) The score is computed automatically by virtual attribute fields that store, for each polygon, its area, weighted value and percentage contribution to the locality total (BGF_contrib), and, for the locality, the totals tot_BGF1 and tot_BGF2 and the final score BGF_final. The project was built for QGIS 2.18.11, uses aerial orthophotos (preferably both summer and winter images, to capture canopy and ground cover) and national base-map web services as background data, and stores all category definitions and weighting factors in editable CSV files [7], [14].

The score is calculated as an area-weighted sum, which is the operational form of Eq. (1):

$$\text{BGF} = [\sum_i (A_i \times f_i) + \sum_i (A_i \times f_i)] / A \quad L + E \quad (2)$$

where A_i is the area (m^2) of surface polygon i of types A1–A9 and f_i its weighting factor; A_j is the area of additional-quality polygon j of types B1–D5 (including tree-canopy area, C1) and f_j its factor; A_L is the total locality area; and E is a fixed connectivity bonus of 0.05, added when the blue-green structures of the locality connect to an existing structure outside it (E1). The default factors of the BGF-QGIS implementation, which are taken from the 2014 Norwegian guidance [6], [7], are listed in Table 1. Because the surface polygons partition the locality, the first sum cannot exceed A_L ; the additional qualities, however, are superimposed on the surfaces and add to the numerator, so that a BGF score can exceed 1.0.

Table 1. Blue-green structures and default weighting factors in BGF-QGIS (after Horvath et al. [7], Appendix 11.1, based on the 2014 BGF guidance [6])

Code	Blue-green structure	Factor
A1	Open permanent water surface that can receive rainwater	1.0
A2	Partially permeable surface (gravel, crushed stone, reinforced grass)	0.3
A3	Impermeable surface draining to vegetated areas or an open drainage magazine	0.2
A4	Impermeable surface draining to a local closed stormwater facility	0.1
A5	Vegetation connected to natural soil or bedrock	1.0
A6	Vegetation not connected to natural soil, soil depth > 80 cm	0.8
A7	Vegetation not connected to natural soil, soil depth 40–80 cm	0.6
A8	Vegetation not connected to natural soil, soil depth 20–40 cm	0.4

A9	Vegetation not connected to natural soil, soil depth 5–20 cm	0.2
B1	Natural edges to water surfaces (additional quality)	0.3
B2	Rain bed or equivalent planted infiltration (additional quality)	0.3
C1	Closed tree canopy, mapped as digitised crown area (additional quality)	1.0
D1	Native vegetation (additional quality)	0.6
D2	Hedges, bushes and multi-stemmed trees > 3 m (additional quality)	0.4
D3	Green walls (additional quality)	0.4
D4	Perennials and other ground cover, excluding lawn (additional quality)	0.3
D5	Contiguous green area > 75 m ² (additional quality)	0.1
E1	Connectivity to an existing blue-green structure outside the locality	+0.05 (fixed)

For the demonstration locality, the documented final score is BGF = 0.871 (Figure 4) [7]. The polygon-level areas and contributions that produce this value are held in the attribute table of the project layer, but they are not tabulated in the published documentation; a category-by-category decomposition of the 0.871 value is therefore not presented here, since it could only be obtained by re-digitising the locality. To make future applications fully reproducible, we recommend, and will adopt for the Bratislava applications, a minimum reporting set consisting of: the locality area and the mapped fraction of that area (MappedArea field); the area, factor, weighted area and percentage contribution of every category; whether the connectivity bonus was applied; the imagery and base-map sources and their dates; and the QGIS and BGF-QGIS versions used.

RESULTS

Findings of the Literature-Based Analysis (Component A)

The literature-based analysis indicates that blue-green infrastructure (BGI), supported by the Blue-Green Factor (BGF) framework, represents a significant approach for improving urban environmental performance and sustainability. The literature analysis confirms that increasing urbanization and the expansion of impermeable surfaces intensify stormwater runoff, reduce natural infiltration, and contribute to flooding and water pollution. In response, BGI has emerged as an effective nature-based solution that integrates ecological and hydrological functions into urban planning systems.

The results show that the Blue-Green Factor provides a structured method for quantifying and evaluating the presence and quality of blue and green elements within urban areas. By incorporating indicators such as vegetation coverage, permeable surfaces, and stormwater retention capacity, the BGF framework enables a systematic assessment of ecological performance at the property level. However, the study also identifies clear methodological limitations in the original Excel-based BGF approach, particularly its reliance on manual area calculations, restriction to single-property analysis, and lack of spatial visualization capabilities. These constraints significantly reduce its applicability in large-scale urban planning and comparative spatial assessment.

The analysis further demonstrates that the evolution of BGF tools, particularly through the development of GIS-based platforms such as QGIS, substantially enhances the applicability and functionality of the method. The integration of spatial datasets, remote sensing imagery, and cadastral information allows for more spatially explicit, scalable, and visually interpretable mapping of blue-green infrastructure. Compared to the original spreadsheet-based model, the QGIS-based approach enables the assessment of entire neighborhoods and urban districts, rather than isolated parcels, thereby supporting more strategic and comprehensive planning decisions.

Overall, the results confirm that the transition from traditional spreadsheet-based BGF assessment to GIS-based spatial analysis represents a significant advancement in urban environmental planning. The combination of theoretical frameworks, spatial

technologies, and nature-based solutions provides a more comprehensive understanding of urban sustainability challenges and offers a practical pathway for improving resilience, climate adaptation, and stormwater management in cities. These are findings about the capabilities of the method as documented in the literature and in the tool documentation; they are not the outcome of an empirical comparison of the two approaches on the same Bratislava site.

Furthermore, the study identifies that the QGIS-based BGF methodology improves the visibility and valuation of urban ecosystem services, which are often overlooked in conventional planning processes. By translating ecological and hydrological characteristics into spatially analyzable data, BGF-QGIS supports evidence-based decision-making and enhances the integration of environmental considerations into urban development strategies. The flexibility of the system also allows adaptation to local conditions by adjusting weighting factors and incorporating additional blue-green elements, making it a versatile tool for diverse urban contexts. This flexibility is particularly relevant in light of the cost-effectiveness caveats discussed in Section 2.4: because the base BGF architecture allows category weights to be adjusted, a municipality that identifies a low-cost/low-performance bias in its own locally adapted scoring scheme is able, at least in principle, to revise those weights, rather than being locked into the original category structure [10].

Demonstration Mapping: Derivation and Interpretation of the BGF Score (Component B)

Applying Eq. (2) and the factors in Table 1, the demonstration locality attains a final BGF of 0.871 (Figure 4). This value should be interpreted as follows. A BGF score is a dimensionless ratio of weighted blue-green area to total locality area, not a percentage of green cover: a score of 0.871 means that the weighted contributions of all mapped surfaces and additional qualities are equivalent to 87.1% of the locality being covered by the highest-weighted surface type (vegetation connected to natural soil, factor 1.0). The same score could be reached by different combinations of measures, for example by a large share of lawn on natural soil, or by a smaller vegetated area combined with substantial tree canopy and rain beds. For this reason, the composition of a score, and not only its magnitude, needs to be reported.

A score is meaningful only relative to a threshold defined within the same scoring scheme. In Oslo, the municipal norm for residential projects adopted by the City Council in 2019 requires a minimum BGF of 0.7 in the dense city and 0.8 in the open city [23], and the norm was revised and extended to further land uses in 2023. Against these reference values, 0.871 would satisfy both thresholds. This comparison is indicative only: the Oslo norm uses its own, later list of measures and weights, which differ from the 2014 factors embedded in BGF-QGIS, and the demonstration locality is an institutional rather than a residential property. No BGF threshold exists in Bratislava, and the score cannot be compared directly with Bratislava's green-area coefficient or with its emerging Ecoindex, which use different categories and scales (Sections 2.2 and 4).

Finally, the score depends on expert-assigned factors rather than on measured performance. Comparative analysis of the Berlin, Stockholm and Oslo indicators shows that the choice of categories

and weights constitutes an implicit valuation of ecosystem services [9], and the Oslo cost-effectiveness evidence shows that such factors can favour low-cost measures [10]. A score of 0.871 therefore indicates that the locality performs well according to the priorities embedded in the BGF, which emphasise stormwater handling and vegetation on natural ground, but it does not by itself indicate how much runoff the locality actually retains. The hydrological meaning of such a score is discussed below.

Interpreting what a BGF score of this magnitude implies for actual hydrological performance requires reference to the independent empirical literature on the individual blue-green elements that such a score typically aggregates. For the vegetated and permeable surface categories that dominate the demonstration locality's mapped area (Figure 4), field and meta-analytic studies of bioretention and rain-garden systems -- broadly comparable to the vegetated, soil-connected surfaces credited under the BGF scoring scheme -- report runoff-volume reductions that commonly range from roughly half to nearly all of the incident rainfall volume, depending on filter-media specification, the ratio of contributing impervious area to facility size, and antecedent soil-moisture conditions [24], [25]. Where green roofs are present, a global meta-analysis of 75 peer-reviewed studies found an average per-event retention rate of approximately 62%, with substrate depth, rainfall intensity, and vegetation cover explaining much of the observed variation [26]; an earlier and still widely cited European synthesis reported a broader range of roughly 27-81% of annual rainfall retained by extensive green roofs [27]. Where open water surfaces or constructed wetland-type elements are credited, the constructed-wetland literature documents substantial pollutant removal [28], although the hydrological attenuation such elements provide in stormwater applications depends strongly on storage volume, hydraulic retention time and seasonal vegetation dynamics. None of these figures can be read directly onto the 0.871 score of the demonstration locality, since the BGF methodology does not itself simulate rainfall-runoff response; however, they provide an independent point of reference suggesting that a locality scoring highly on BGF's vegetated and permeable-surface categories is, in aggregate, likely to be associated with meaningful runoff retention, even though the precise volumetric performance would need to be confirmed through dynamic hydrological modelling of the kind discussed in Section 2.5.

Bratislava Governance Context (Component C)

Bratislava's documented governance arrangements provide the context in which a BGF-type instrument would operate.



Figure 4. BGF-QGIS map of the demonstration locality (property of the County Governor, Ås, Norway; tutorial locality of the BGF-QGIS documentation) after digitising blue-green surfaces and additional qualities, with final BGF = 0.871 (top), and the corresponding tree-canopy and vegetation layer (bottom). Reproduced from Horvath et al. [7], NINA Report 1445, which may be freely cited with acknowledgement of the source.

According to Belčáková et al. [15], residents can take over the care of selected public green areas through the programme 'Adopt Greenery'; the city has operated a small-grant scheme co-financing 50% of resident-built rainwater-retention elements costing up to EUR 1,000; the city's public website serves as an integrated platform for communicating residents' demands and proposals; and the pilot programme 'Bratislava prepares for climate change' (2014–2016), co-financed by the EEA and Norway Grants, implemented more than 20 greenery and rainwater-retention projects. The same study documents constraints that are directly relevant to BGF implementation: the absence of an up-to-date greenery master plan, fragmented and partly unregistered land ownership, limited staffing of the Municipal Architect Office, and competences split between the city and its 17 districts [15]. These instruments and constraints are reported as documented; their effectiveness was not evaluated in this study. Taken together, they suggest that a BGF-QGIS approach in Bratislava would be most useful as a shared spatial evidence base for the city and its districts, and that its adoption would depend on institutional coordination and ownership data as much as on the mapping technique itself.

DISCUSSION

The findings of this study highlight the increasing importance of integrated blue-green planning tools in addressing complex urban sustainability challenges. The analysis of blue-green infrastructure (BGI), the Blue-Green Factor (BGF), and GIS-based approaches such as QGIS demonstrates a clear shift from traditional, fragmented urban planning methods toward more holistic and spatially informed environmental assessment systems. A key outcome of the study is the recognition that the original BGF methodology, while effective at the property scale, is limited in its capacity to support large-scale urban analysis. Its reliance on manual calculations and spreadsheet-based evaluation restricts its usability in contemporary urban planning contexts where spatial complexity, data availability, and multi-property interactions must be considered. In contrast, GIS-based tools such as QGIS significantly improve the analytical capacity of BGF by enabling spatial visualization, multi-layer data integration, and scalable environmental assessment across neighbourhoods and entire urban districts.

The study also demonstrates that the evolution of BGF tools reflects a broader transformation in urban environmental governance. The transition from Excel-based calculations to mobile applications (the Android BGF Calculator [7]) and ultimately to GIS platforms illustrates a progressive enhancement in both technical capability and planning relevance. QGIS-based BGF mapping allows for the integration of remote sensing data, cadastral boundaries, and urban design datasets, thereby improving the spatial

transparency and applicability of blue-green assessments. This shift supports more evidence-based decision-making and strengthens the role of ecological indicators in urban planning processes. The inclusion of Bratislava as a contextual case further reinforces the practical relevance of blue-green planning frameworks. Municipal initiatives such as participatory green space programs, rainwater retention incentives, and decentralized green infrastructure management demonstrate how policy instruments can complement technical tools. These initiatives align closely with the objectives of the Metropolitan Institute of Bratislava (MIB), which promotes data-driven and sustainability-oriented urban development [17].

Bratislava's emerging Ecoindex (Ekoindex) is the most direct local counterpart to the BGF. It was developed by MIB in spring 2024 as a spatial-planning tool that evaluates the quality as well as the quantity of green-blue infrastructure, crediting measures such as water-retention areas, green roofs, green facades and measures supporting biodiversity; it has been tested in the Mlynské nivy development area and is intended over time to replace the quantity-based KZ [17]. The Ecoindex is part of Decree No. 392/2023 Coll. of the Office for Spatial Planning and Construction of the Slovak Republic, under which Bratislava and Košice may apply it in their metropolitan zoning plans [18], [19]. Because the Ecoindex is still being introduced, its effects on development outcomes cannot yet be assessed, and the comparison here is limited to design features. Both instruments are area-weighted, performance-based indicators of the Biotope Area Factor lineage [8], [9]. The Ecoindex is designed as a statutory regulatory parameter in zoning, whereas BGF-QGIS is primarily an assessment and mapping environment whose categories and weights can be edited [7]. The two are therefore complementary rather than competing: a QGIS workflow of the kind described in Section 2.6 could, in principle, be configured with Ecoindex categories and factors to map compliance across whole districts, while retaining the possibility of periodic re-weighting that the safe-to-fail logic of adaptive urban planning recommends [29].

Overall, the discussion confirms that combining BGF methodology with GIS technologies and urban policy instruments such as Ecoindex creates a more comprehensive framework for sustainable urban development. This integration enhances the ability of planners and decision-makers to address environmental challenges such as stormwater runoff, heat island effects, and biodiversity loss in a coordinated and measurable way [4], [13].

Placing Bratislava's experience alongside the wider international literature on performance-based green area indicators (Section 2.3) sharpens several of the conclusions above. First, the comparative analysis of Berlin's Biotope Area Factor, Stockholm's Green Area Factor, and Oslo's Blue-Green Factor shows that these tools differ not only in name but in the ecosystem services they implicitly prioritise, with stormwater-oriented variants such as Oslo's BGF placing comparatively more weight on runoff retention than biodiversity-oriented variants [9]. This suggests that any future formal adoption of a BGF-type instrument in Bratislava should begin with an explicit decision about which ecosystem services -- stormwater retention, biodiversity, heat mitigation, or some weighted combination -- the local scoring scheme is intended to prioritise, rather than importing a foreign weighting scheme unmodified. Second, the cost-effectiveness evidence from Oslo's BGF is a useful cautionary reference point: because that evidence shows a BGF-type score can be met with structurally simple, low-cost vegetation at the expense of more hydrologically effective measures unless the scoring weights are specifically designed to prevent this [10], Bratislava's Municipal Architect Office and any future evaluators of a local BGF-QGIS scheme would be well advised to review measure-level scoring weights against independent hydrological and ecological evidence rather than treating a high aggregate score as self-evidently indicating strong stormwater performance.

The findings also connect to the broader theoretical framing of blue-green infrastructure as part of a transition toward water-sensitive cities. Water-sensitive urban design treats water management not as a narrow drainage-engineering problem but as an integrated planning discipline spanning urban design, ecology, and infrastructure engineering [30], and the BGF-QGIS approach examined in this study is consistent with that framing: by embedding a stormwater-relevant scoring metric directly within spatial planning datasets used for cadastral and design purposes, it helps ensure that water-sensitive considerations are visible to planners and developers at the point where site-level design decisions are actually made, rather than being addressed separately by drainage engineers after the urban form has already been fixed. This is reinforced by the social-ecological-technological systems perspective on urban green and blue infrastructure, which emphasises that the benefits delivered by a given green or blue element depend not only on its biophysical characteristics but on the surrounding institutional, social, and technological context in which it is embedded and maintained [13]. Bratislava's combination of a technical mapping tool (QGIS-based BGF digitising) with social and institutional instruments (the "Adopt Greenery" participatory programme, the small-grant scheme for rainwater retention, and decentralised district-level management [15]) is, in this framing, precisely the kind of multi-layered arrangement that the literature suggests is necessary for blue-green infrastructure to deliver its intended benefits in practice, rather than remaining a purely technical mapping exercise.

Finally, the discussion should acknowledge a limitation shared across BGF-type indicators generally: as a static, area-weighted scoring method, BGF does not itself account for the non-stationary rainfall conditions increasingly documented in the climate literature [11]. A locality that scores well against current BGF thresholds, calibrated implicitly against historical rainfall assumptions, may not retain the same relative performance under future, more intense rainfall regimes unless the underlying design storms and category weightings are periodically revisited. This points toward a natural direction for future research combining BGF-type spatial screening with the kind of non-stationary design-storm analysis discussed in Section 1, so that blue-green infrastructure scoring tools remain aligned with a changing rather than a historical climate baseline.

The present study also has specific limitations. The quantitative demonstration relies on a documented reference locality in Norway rather than on original mapping in Bratislava, so no empirical BGF values for Bratislava are reported; the category-level composition of the demonstration score is not available from the published documentation; the default 2014 Norwegian weights were not calibrated to Bratislava's climate, soils or regulatory priorities, and no sensitivity analysis of the weights was performed; and the mapped categories were not validated in the field. In addition, the literature component is a narrative rather than a systematic review. These limitations define the scope of the conclusions, which concern the method and its transferability rather than the blue-green performance of any Bratislava locality.

CONCLUSION

This study examined blue-green infrastructure, focusing on the Blue-Green Factor (BGF) as a theoretical and practical tool for supporting sustainable urban development, with particular emphasis on GIS-based mapping in QGIS and urban planning applications in Bratislava. The analysis indicates that while traditional BGF methodologies provide a useful foundation for evaluating ecological and hydrological performance at the property level, they are limited in their ability to support large-scale spatial planning and integrated urban analysis. The transition toward GIS-based approaches, particularly through QGIS, significantly improves the functionality, scalability, and spatial transparency of BGF assessment. By enabling spatial visualization and multi-layer environmental

analysis, QGIS enhances the applicability of blue-green infrastructure planning in contemporary urban contexts. This advancement allows for more comprehensive evaluation of urban ecosystems and supports data-driven decision-making in sustainable city development.

The study further highlights the relevance of municipal initiatives in Bratislava, including participatory green space programs and climate adaptation strategies led by urban institutions such as the Metropolitan Institute of Bratislava. The ongoing introduction of the Ecoindex, which is intended to complement and eventually replace the quantity-based green-area coefficient, demonstrates a shift toward ecological planning frameworks that assess the quality as well as the quantity of green and blue areas [17]. Placed within the wider international lineage of performance-based green area indicators -- from Berlin's Biotope Area Factor through Malmö, Stockholm, Helsinki, Seattle, and Oslo -- Bratislava's exploration of BGF-QGIS mapping represents a locally adapted contribution to a well-established but still actively evolving international practice, one whose weighting assumptions and cost-effectiveness properties continue to be refined by ongoing research [8], [9], [10].

In conclusion, the integration of BGF, GIS technologies, and ecological planning tools provides a robust and adaptable framework for improving urban resilience, and addressing the challenges of climate change. Future urban planning strategies should continue to develop and refine these integrated approaches to support long-term sustainability and climate-adaptive urban transformation. Four priorities for future work follow from the analysis. First, the BGF-QGIS workflow documented in Section 2.6 should be applied to one or more Bratislava localities selected by explicit criteria (for example, contrasting inner-city and housing-estate typologies within a single municipal district), reporting the full category-level decomposition of each score so that the results are reproducible. Second, any formal adoption of a BGF-type scoring scheme in Bratislava, or the calibration of the Ecoindex, should be accompanied by an explicit, locally justified weighting rationale informed by the comparative and cost-effectiveness evidence reviewed in this study, together with a sensitivity analysis of the weights, rather than an unmodified import of another city's category weights. Third, static BGF scores should, where resources allow, be complemented by dynamic hydrological modelling of priority localities, so that the screening function of BGF-QGIS is linked to physically based estimates of runoff and peak-flow performance. Fourth, BGF thresholds and design assumptions should be revisited periodically against non-stationary climate projections, to ensure that a tool calibrated against historical rainfall conditions continues to represent a meaningful standard as Bratislava's climate changes.

DATA AVAILABILITY

The BGF-QGIS project structure, category definitions and default weighting factors used in Section 2.6 are openly available from the tool repository cited in [7]. No new spatial data were generated in this study.

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