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Integrating AI and spatial analysis for resilient and inclusive 15-minute cities: A case study of Gdańsk

Anahita Azadgar [a], Marichela Sepe [b], Artur Gańcza [c], Piotr Lorens [d], Giulia Luciani [e], Lucyna Nyka [a,*]

[a] Department of Urban Architecture and Waterscapes, Faculty of Architecture, Gdansk University of Technology, Narutowicza 11/12, 80-233, Gdansk, Poland
[b] Department of Civil, Building and Environmental Engineering, Sapienza University of Rome, Via Eudossiana 18, 00184, Rome, Italy
[c] Department of Signals and Systems, Faculty of Electronics, Telecommunications and Informatics, Gdansk University of Technology, Narutowicza 11/12, 80-233, Gdansk, Poland
[d] Department of Urban Design and Regional Planning, Faculty of Architecture, Gdansk University of Technology, Narutowicza 11/12, 80-233, Gdansk, Poland
[e] Department of Architecture, University of Florence, Via Micheli 2, 50121, Florence, Italy

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ABSTRACT

This study explores the application of artificial intelligence (AI) and geospatial tools to design 15-min cities, focusing on proximity, public space quality, environmental resilience, and inclusion. Using the post-industrial Young City district in Gdańsk, Poland, as a case study, the research integrates semantic segmentation (DeepLabv3) and AI-driven object detection for evaluating public space quality, flood simulation modeling (InVEST UFRM) for climate resilience, and network analysis using adjusted walking speeds (2.95 km/h) to capture the needs of vulnerable populations. By identifying "hotspots" with compounded deficits in access to urban amenities, public space quality, and resilience, the study provides a replicable, data-informed tool for guiding equitable urban transformation. The findings reveal critical spatial and environmental disparities, particularly in former fence-line neighborhoods in Gdańsk, which remain underserved despite ongoing urban redevelopment. The proposed framework offers practical insights for mainstreaming inclusive adaptation strategies into planning policies and contributes to the evolving discourse on operationalizing the 15-min city (FMC) concept in complex contexts.

1. Introduction

Urban sprawl remains one of the most pressing challenges in contemporary urban planning, characterized by unchecked spatial expansion that consumes land, escalates energy demands, and fragments ecosystems (Zhao et al., 2018). Beyond its environmental toll—evident in habitat loss, carbon emissions, and air pollution—sprawl exacerbates socioeconomic inequities by isolating communities, limiting access to essential services, and burdening municipalities with inefficient infrastructure costs (Genovese et al., 2023; Han, 2020). Vulnerable populations, particularly those without private vehicles, face disproportionate barriers to healthcare, education, and employment, perpetuating cycles of marginalization (Enwin & Ikiriko, 2023; Magina et al., 2024).

In response, compact urban development has emerged as a sustainable alternative, prioritizing density, mixed land use, and pedestrian-centric design to reduce car dependency and enhance livability (Fan & Chapman, 2024; Mun et al., 2025). Among these frameworks, the 15-min city (FMC) concept has emerged as a transformative model, advocating for neighborhoods where daily necessities – work, education, shopping, healthcare, and leisure – are accessible within a 15-min walk or bike ride (Moreno et al., 2021; Pozoukidou & Angelidou, 2022). By decentralizing urban functions, the FMC aims to curb sprawl, lower carbon footprints, and foster social cohesion (Sdoukopoulos et al., 2024).

Despite its adoption by many cities, the FMC model's implementation still reveals critical gaps. For instance, while studies emphasize proximity metrics, the model's reliance on standardized walking speeds (3.2–5 km/h) often excludes seniors, children, and individuals with disabilities, thereby undermining its inclusivity (Akrami et al., 2024; Liu

* Corresponding author.
E-mail addresses: anahita.azadgar@pg.edu.pl (A. Azadgar), marichela.sepe@uniroma1.it (M. Sepe), artur.gancza@pg.edu.pl (A. Gańcza), giulia.luciani@unifi.it (G. Luciani), lucyna.nyka@pg.edu.pl (L. Nyka).

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et al., 2024).

Furthermore, although the FMC focuses on accessibility and proximity to local amenities, research on the quality of public spaces in this model is still limited. These spaces are essential for social interaction, safety, and comfort, and their design significantly influences residents' perceptions of livability (Abdelkarim et al., 2023). While the FMC aims to promote diverse, high-quality urban spaces (Allam et al., 2022), most studies continue to prioritize accessibility over qualitative dimensions (Graells-Garrido et al., 2021; Patimisco et al., 2024). To ensure effective and equitable implementation, enhanced frameworks that integrate both accessibility and spatial quality are urgently needed (Biraghi et al., 2025; Sepe, 2010). Moreover, environmental considerations often remain peripheral: while green spaces are widely recognized for their role in fostering sustainable cities and enhancing human well-being, and access to urban greenery is often incorporated into proximity analysis, FMC studies rarely incorporate nature-based risk mitigation strategies for climate-induced hazards such as urban heat islands or flooding (Azadgar, Luciani, & Nyka, 2025; Kozar et al., 2024).

These identified gaps highlight that while the foundational premise of the 15-min city (FMC) concept is rooted in proximity, a purely distance-based understanding of proximity presents significant limitations in achieving a truly equitable, resilient, and livable urban environment. Our framework extends this foundational concept by arguing that the effectiveness and sustainability of proximity are profoundly influenced by three interconnected dimensions: spatial quality, environmental resilience, and socio-spatial inclusivity. While these aspects have individually been highlighted in various urban studies, their synergistic integration within a unified FMC framework is crucial. Neglecting any of these elements risks undermining the very benefits that the 15-min city seeks to deliver, as proximity alone does not guarantee a high quality of life, protection from climate risks, or equitable access for all population segments.

The opportunities to enhance existing frameworks and perform complex analyses are deeply linked to the advancements in digital technologies such as computer vision, geospatial network analysis, and multi-criteria optimization, which are reshaping how cities are diagnosed and planned (Kaya et al., 2025; Zboinska et al., 2015). Tools like Google Street View (GSV), when combined with deep neural networks, allow for scalable and automated assessments of public space quality – surpassing the limitations of time-consuming manual field surveys (Biljecki and Ito, 2021). Network-based spatial analysis improves the precision of accessibility evaluations by accounting for real travel paths rather than theoretical or buffer-based distances. Furthermore, the accessibility of software models for mapping and valuing the ecosystem services provides tools for assessing climate-related environmental risks. When integrated with urban planning, these digital methods enable planners to identify critical gaps, prioritize interventions, and support more equitable and resilient urban transformations.

In response to the research gaps and the emerging potential of digital analytical tools, this study advances the 15-min city (FMC) discourse by proposing a novel, extended framework that still places proximity in the center of study and adds to the existing frameworks. The proposed framework integrates proximity and AI-driven spatial analytics with inclusivity-oriented governance and environmental resilience. Using Gdańsk's post-shipyard district and its vicinities as a case study, we introduce three key innovations:

- Advancement of the 15-Minute City Framework: We enhance the FMC model by integrating spatial quality, environmental resilience, and inclusive proximity metrics into a unified analytical approach.
- AI-Driven Spatial Quality Assessment: Leveraging Google Street View imagery and deep learning models (DeepLabv3, Faster R-CNN), we automate evaluations of public space quality – addressing gaps in traditional fieldwork methods.
- Multi-Criteria Hotspot Mapping: By overlaying flood risk, proximity gaps, and spatial quality deficiencies, we identify priority intervention zones – a methodology directly applicable to policymakers managing urban transitions.

The study demonstrates the potential of combining AI and geospatial tools for multi-dimensional urban analysis. Specifically, we employ semantic segmentation and Faster R-CNN for object detection in the Street View Imagery (SVI) dataset, flood simulation modeling (InVEST UFRM) to acquire environmental data, and conduct geospatial network analysis to construct a layered diagnostic toolkit. This methodological innovation supports data integration and enhances the policy relevance of the FMC framework by facilitating more inclusive, climate-aware urban planning.

2. Research review

2.1. Proximity as the foundation of the 15-minute city concept

Proximity stands as the foundational principle of the 15-min city (FMC) concept, which seeks to reorganize urban spaces to enhance sustainability and quality of life. This urban planning model, conceptualized by Carlos Moreno, fundamentally redefines urban accessibility through time-based proximity rather than traditional distance metrics, measuring the minutes needed to walk or cycle to essential urban functions (Vich et al., 2023). The operationalization of proximity in FMC research employs sophisticated spatial analysis methods including isochrone mapping, network-based routing algorithms, and cumulative opportunity measures to quantify accessibility (Petrova-Antonova et al., 2025). For instance, studies have utilized grid-based approaches with 100 × 100 m cells combined with OpenStreetMap routing to calculate walking minutes to everyday destinations (Israel et al., 2026), while others have implemented graph-based pedestrian travel time calculations to derive quantitative indices of 15-min urban character (Barbieri et al., 2023). These methodological approaches consistently demonstrate that proximity is not merely a theoretical construct but a measurable spatial condition that can be systematically evaluated across different urban contexts, with research showing significant variation in accessibility outcomes – such as Vancouver's finding that less than 1% of the population lacks cycling access to grocery stores within 15 min, while approximately one-fifth lack walking access when accounting for older pedestrian speeds (Hosford et al., 2022).

With the advancement of GIS tools, network-based spatial analysis has become a cornerstone methodology for evaluating accessibility within the FMC framework, offering precision and practicality that surpass circular buffering methods. Unlike circular buffers, which assume uniform access in all directions and disregard physical or legal barriers, network analysis measures accessibility along actual travel paths such as roadways, sidewalks, and transit routes. This approach accounts for obstacles like walls, highways, or restricted zones, providing a more realistic representation of urban accessibility (Badland et al., 2013; Wolff, 2021). By incorporating multimodal routes – walking, cycling, driving, or public transit – network analysis enables tailored insights into how different transportation modes influence accessibility to essential services. For example, it can precisely determine travel times to amenities such as shops or schools based on actual street networks, supporting optimal location decisions for public services (Bajjali, 2023; Wen et al., 2023).

Advanced computational tools such as Urban Network Analysis (UNA), Configurbanist, CityMetrics, and Urbano have emerged as powerful instruments for simulating and analyzing accessibility within urban areas. These tools utilize clustering algorithms to identify patterns in urban mobility and spatial relationships at granular levels. They enable urban planners to evaluate proximity at the building level and optimize service delivery through practical network configurations (García-Palomares et al., 2018; Ye et al., 2018). The superiority of network-based spatial analysis lies in its ability to reflect real-world conditions. Physical and legal barriers are integrated into the analysis, ensuring accessibility evaluations are grounded in practical travel paths rather than theoretical radii. For instance, in Portland's 20-min neighborhood plan, network analysis using pedestrian-accessible streets highlighted that limited sidewalk infrastructure and fragmented connectivity hindered accessblity in neighborhoods (Simon, 2022) – barriers that circular buffer methods would have overlooked.

Empirical studies across diverse cities have revealed both the potential and limitations of proximity-based planning: Porto reported that 84% and 100% of residents live within a 15-min walking and cycling distance of urban green spaces respectively, yet cycling remains marginal due to fragmented infrastructure, demonstrating that spatial proximity must be complemented by appropriate physical infrastructure to translate potential accessibility into realized active mobility (Almeida & Fonseca, 2025). Additionally, Biraghi et al. (2025) argues that the effective 15-min city implementation requires balancing quantitative proximity with qualitative diversity of urban functions that are accessible within 15 min walk or bike, as proximity alone without adequate service variety cannot achieve the model's resilience and wellbeing goals. Furthermore, multi-method comparative analyses, such as Barcelona's three-method geospatial assessment, have shown that different operationalizations of proximity yield method-specific strengths and limitations, underscoring the need for context-sensitive approaches that account for local morphology, demographics, and mobility patterns when applying the 15-min city framework (Vich et al., 2023). Thus, despite complexities, proximity serves not only as the conceptual cornerstone but also as the practical metric through which planners can assess and enhance urban accessibility and livability.

To sum up, the centrality of proximity to the 15-min city framework extends beyond mere spatial measurement to encompass its role as the enabling condition for active mobility, sustainability, and equitable urban development. Network-based spatial analysis ensures that the FMC framework is aspirational and actionable by prioritizing real-world travel dynamics over theoretical proximity metrics. It provides urban planners with the tools needed to create highly accessible cities where proximity to amenities is matched by equitable access across diverse populations. This methodology represents a significant step forward in designing efficient and inclusive cities.

2.2. *Livability and public space quality*

While proximity metrics provide the quantitative foundation for the 15-min city concept, emerging scholarship has increasingly emphasized that mere physical accessibility is insufficient without attention to the qualitative dimensions of public spaces and urban environments (Distefano & Leonardi, 2023; Barratt & Swetnam, 2022; Evans, 2009). Studies have highlighted that successful implementation of the 15-min city depends on creating not just proximate but also attractive, welcoming, and socially vibrant public spaces that encourage community interaction and support diverse activities (Allam et al., 2024). This qualitative turn in the FMC discourse recognizes that human-centered urban design requires understanding how people perceive, experience, and interact with their local environments, moving beyond accessibility metrics to consider factors like street vitality, social cohesion, placemaking, and the quality of the pedestrian experience (Kyriakidis et al., 2024; Zhou et al., 2023).

Public spaces are vital hubs for social interaction, physical activity, cultural expression, and mental restoration. They contribute to environmental sustainability by mitigating urban heat islands, improving air quality, and supporting biodiversity through green infrastructure. Socially, they foster equity by providing inclusive environments accommodating diverse populations, including children, seniors, and individuals with disabilities. Features, such as seating availability, green space quality, architectural diversity, well-maintained pathways, and opportunities for social encounter ensure accessibility for all users (McCay, 2017). Moreover, well-designed public spaces enhance safety and comfort through thoughtful elements like adequate lighting, active frontages (e.g., cafés or retail), and visible signage that encourages prolonged use while deterring antisocial behavior (Gehl, 2011).

Theoretical frameworks rooted in urban studies, livability research, and environmental psychology, provide valuable guidance for enhancing public space quality. Saunders' (2017) Healthy Streets framework integrates ten indicators related to pedestrian prioritization, noise reduction, and air quality improvements – to create healthier, more inclusive urban environments. Similarly, Richard Crappsley's focus on street design emphasizes the integration of cycling lanes, green buffers, and public art to enhance walkability and transform streets into vibrant social ecosystems rather than mere transit corridors (Crappsley, 2017). McCay's (2017) Mind the Gaps emphasizes the need for accessible green spaces that facilitate social interaction and foster physical activity while criticizing the disconnect between urban planning policies and lived experiences. Recent research has emphasized that qualitative dimensions of urban space are particularly critical for vulnerable populations, including elderly residents, children, and people with disabilities, whose mobility and use of public space are especially sensitive to environmental quality factors beyond mere proximity (Tabatabaei, 2025).

Case studies further underscore the transformative potential of high-quality public spaces. Barcelona's Superblocks initiative, for example, reclaims road space from vehicles to establish pedestrian-friendly zones with green corridors – efforts that have significantly improved air quality and boosted pedestrian activity (Sdoukopoulos et al., 2024). In Belgium, transformations in Namur, Wavre, and La Louvière demonstrate how underutilized spaces can be reimagined into vibrant public areas, fostering stronger community engagement and spatial vitality (Cilliers & Timmermans, 2016). Similarly, in Shanghai, the redevelopment of the Huangpu River waterfront and community-scale micro-regeneration projects illustrate the importance of people-centered design and high-quality public environments in urban renewal efforts (Zhu, 2023). In Berlin, the Mediaspree area exemplifies the creation of inclusive, multifunctional public spaces that support mixed-use development and reflect the city's commitment to social diversity and environmental integration (Lee, 2022). These initiatives showcase how well-designed public spaces can serve as symbols of urban regeneration, cultural expression, and improved quality of life.

Ultimately, the FMC model is increasingly recognized to evolve beyond simple proximity metrics to prioritize the quality of public spaces as a core pillar of urban livability. Methodologically, existing frameworks for assessing public space quality often rely on qualitative techniques such as walkability audits, community engagement processes, and experiential mapping to capture the lived experience of urban neighborhoods. However, due to their inherent complexity, these qualitative methods have rarely been combined with quantitative proximity analysis. This paper aims to address this research gap utilizing AI and advanced digital tools. By integrating considerations of quality alongside accessibility metrics within urban planning processes, cities can create dynamic public spaces that enhance well-being while addressing contemporary challenges such as climate change and socio-spatial inequities.

2.3. *Environmental assessment in the 15-minute city approach*

Environmental assessments are pivotal in advancing the 15-min city (FMC) framework, enabling urban planners to balance accessibility with ecological resilience, which is particularly important in the context of climate-induced risks. These assessments often integrate environmental, social, and economic dimensions, leveraging technologies such as Digital Twins, IoT, and machine learning (ML) to optimize land use, reduce carbon footprints, and enhance decision-making (Allam et al., 2022a; Azadgar et al., 2025). By prioritizing proximity, the FMC model inherently reduces reliance on long commutes – a critical strategy given that transportation accounts for 14% of global emissions, with road vehicles contributing 72% of this share. This approach lowers greenhouse gas emissions and supports sustainable mobility solutions like shared bikes and e-scooters, which decrease car dependency while promoting active travel (Pozoukidou & Chatziyiannaki, 2021).

However, while existing research emphasizes energy efficiency and resource management, it often overlooks location-specific environmental hazards such as flooding, heatwaves, or air pollution, limiting the framework's adaptability to diverse urban contexts. Therefore, research studies on environmental considerations or climate-related challenges in the context of the FMC are scarce. Recent scholarship has begun to address this gap: de Rijke et al. (2025) systematically reviewed blue-green infrastructure's role in mitigating climate-induced hazards within x-minute cities, highlighting extreme heat as a key challenge for public space quality; Chen and He (2022) developed a framework to integrate urban heat adaptation into 15-min city planning; and Giles-Corti et al. (2023) argued that delivering 15-min cities must include climate mitigation and nature-based solutions to ensure neighborhood-scale resilience. A study presented by Shartova et al. (2024) demonstrates the FMC's potential to mitigate heat vulnerability by improving access to green spaces and cooling centers, showcasing how tailored interventions can enhance urban resilience during extreme weather events.

Yet despite this growing attention to urban heat islands, the critical issue of flooding and urban inundation – hazards that can profoundly disrupt pedestrian and cycling networks, and significantly diminish space quality – is largely under-examined in proximity-based planning literature. Empirical studies from other urban contexts clearly substantiate these multifaceted impacts. For instance, Opach et al. (2023) demonstrated through user testing in Trondheim that accumulated water on sidewalks and footpaths significantly affects pedestrian route choices and the usability of walking infrastructure. Morganti et al. (2022) examined pluvial flood risks specifically in Mediterranean compact cities, revealing the vulnerabilities of dense, walkable fabrics to inundation. Further research, such as that by Dal Cin, Hooimeijer and Silva, 2021, has explored how urban flooding can impair walkability, while Nyka and Burda (2020) have employed scenario modeling to assess public space continuities under different water levels and, in a subsequent study (Burda & Nyka, 2023), they identified main morphological typologies of public spaces related to water and therefore susceptible to climate-induced risks.

This gap underscores the need for environmental evaluations that address not only generalized sustainability goals but also localized risks. Innovative hydrological modeling and digital planning support tools are emerging which facilitate bridging this gap. By embedding hazard-specific evaluations into the FMC framework, cities can transition from generic sustainability targets to actionable, context-responsive resilience strategies. This evolution ensures that the 15-min city model not only enhances accessibility but also serves as a tool for equitable climate adaptation, addressing the unique challenges of diverse urban environments through innovative, inclusive planning.

2.4. Bridging research gaps: inclusivity, public space quality, environment, and AI tools

The integration of these three dimensions – proximity oriented toward socio-spatial inclusivity, public space quality, and environmental resilience – is not merely additive but synergistic, designed to address the complex, multifaceted challenges inherent in contemporary urban development. Spatial quality ensures that accessible areas are also desirable, functional, and aesthetically pleasing, fostering social interaction and well-being rather than just physical access to poorly maintained or unsafe spaces. Environmental resilience moves beyond general sustainability goals by embedding localized climate risk assessments, such as heat island threats or flood vulnerability, directly into the accessibility framework, recognizing that an accessible area is only truly functional if it is also protected from environmental hazards. Crucially, socio-spatial inclusivity refines the concept of proximity by accounting for diverse mobilities and socio-economic barriers, ensuring that the 15-min promise is genuinely achievable and beneficial for historically marginalized populations and those with specific needs, rather than disproportionately favoring specific demographics. Together, these three dimensions transform the FMC from a metric of mere distance into a holistic strategy for creating robust, equitable, and adaptable urban futures.

This study, while building on existing research, is aimed to enhance FMC frameworks. It shows that with the use of AI and digital tools it is feasible to process complex data, and integrate new the sets of components to be analyzed, adding to the most commonly used in the FMC models proximity analysis, much needed for achieving urban livability public spaces quality and local climate induced environmental risks.

3. Methods

The research integrates AI-driven object detection and semantic segmentation with traditional GIS methodologies to assess: i) amenity coverage, including public transportation and green infrastructure accessibility; ii) public space quality; and iii) flood risk assessment. It employs this multi-faceted methodology to evaluate the applicability of the 15-min city (FMC) framework in Gdańsk's post-shipyard area and its vicinities.

The methodology is divided into three phases, each leveraging advanced computational tools and analytical techniques to assess the area's alignment with the proposed extended FMC principles comprehensively. First, a network analysis is performed using QGIS tools to evaluate accessibility to key amenities such as grocery stores, healthcare, and recreational spaces, based on a lower than standard walking speed. Network analysis is also applied to assess public transportation proximity, as one of key amenities. Second, public space quality is analyzed by processing GSV images through deep learning models to calculate segmentation, detection, and visual indicators. Finally, we assess urban flood risk using the InVEST (Integrated Valuation of Ecosystem Services and Trade-Offs) UFRM (Urban Flood Risk Mitigation) model, incorporating land cover, soil properties, and runoff data to identify vulnerable areas.

The findings from all three phases – network analysis, public space quality evaluation, and flood risk assessment – were overlaid to identify hotspots, i.e., areas where the combined indicators of accessibility, environmental resilience, and spatial quality revealed the lowest scores. These locations were designated as zones of deficiency, requiring targeted attention and tailored improvement strategies.

3.1. Network analysis for amenity and public transport proximity

The network based spatial analysis with the intention of evaluating the proximity to different amenities within the case study was done using the QGIS Network Analysis Toolbox 3, shortly referred to as (QNEAT3). The points of the amenities were obtained using quickOSM tool in QGIS. In this study, a walking speed of 0.82 m/s (2,96 km/h) was selected to account for populations with slower mobility, such as seniors, children, and individuals with physical disabilities. This speed, identified as a 'slow pace' in meta-analyses of walking speeds in healthy adults (Murtagh et al., 2020), ensures a more inclusive and realistic assessment of urban accessibility and public space usability. By accounting for slower walking speeds, the study better reflects the mobility needs of diverse population groups, thereby reinforcing the principles of inclusivity embedded in contemporary urban planning.

Using the QNEAT3 shortest path network analysis tools, accessibility was evaluated by identifying locations reachable within a maximum network distance of 738 m from each amenity and public transport stop. This distance corresponds to a 15-min walking threshold assuming a walking speed of 0.82 m/s. The analysis was conducted along the street network, ensuring that accessibility was assessed based on actual walkable routes rather than straight-line distances.

Table 1 represents the urban functions and services which were included in proximity assessment. To evaluate the 15-min city concept in relation to urban amenities, we focused on key services that significantly impact accessibility and urban diversity. Grocery retail, including supermarkets, convenience stores, and bakeries, was prioritized as access to essential shopping facilities is a fundamental urban service (Kesarovski & Hernández-Palacio, 2022). Educational facilities, specifically schools, were included due to their role in addressing spatial inequalities in education at the micro-scale level (Ferrer-Ortiz et al., 2022). Food services such as cafés and restaurants are crucial, as their increased presence can notably enhance walkability for most residents (Huang & Khalil, 2023). Health and well-being services, including clinics, medical practices, and veterinary services, were incorporated to ensure adequate healthcare access, which is vital for spatial planning in line with the 15-min city model (Song et al., 2022). Religious and worship services were considered significant for walkable urban planning, as they cater to the needs of communities (Verma et al., 2019). Recreational spaces, such as gardens, parks, and areas designated for recreational land use, were chosen due to their importance in promoting a healthy city environment, particularly for older adults (Ulloa-Leon et al., 2023). Additionally, cultural and artistic venues, including museums, libraries, and artworks, contribute to the vibrancy and diversity of urban life, supporting cultural diffusion and enhancing city connectivity (Bertoni, Dubini and Monti, 2021). Lastly, the inclusion of public transportation hubs, such as tram and bus stops, was essential to facilitate efficient mobility within the 15-min framework.

For each amenity and public transport category listed in Table 1, shortest-path network analysis was performed using QNEAT3 to identify locations reachable within a maximum network distance of 738 m. The resulting outputs were stored as vector-based network reachability layers representing the spatial extent accessible within the 15-min walking threshold. These individual amenity layers were subsequently combined using a union operation in QGIS, producing a single composite layer in which overlapping accessibility extents were preserved. The composite layer was then intersected with the study area boundary, and an attribute field was calculated to record, for each spatial unit, the number of amenity and public transport layers present, ranging from 0 to 8.

3.2. Urban space quality evaluation

An automated approach was employed to assess the quality of public spaces within the study area using GSV imagery. 600 points were randomly generated within the case study area, and panoramic photos were downloaded via the GSV Static API due to its extensive coverage.[1] After preprocessing—removing duplicate images and those depicting non-landscape scenes—198 photos remained for analysis. These images were biased toward road-adjacent spaces due to GSV's data collection methods but provided sufficient diversity for evaluating spatial quality indicators. This refined dataset was then used to calculate the indicators following a procedure applied by Chen and Biljecki (2023). The indicators fall into three main categories: segmentation-based, detection-based, and visual.

To assess the spatial quality indicators across the case study area, object detection and semantic segmentation are applied to the Street View Imagery (SVI) dataset through an automated methodology. Object detection identifies objects such as bicycles, while semantic segmentation categorizes image regions into key features like sky, road, greenery, buildings, and other elements, quantifying their proportions within each image. This analysis enables an objective breakdown of the visual and structural attributes of public open spaces, providing insights into factors such as presence of greenery and natural elements such urban waters, accessibility, and aesthetic appeal. Together, these steps exemplify the use of computer vision techniques to produce a data-driven assessment of urban quality, facilitating targeted urban planning and improvement efforts based on observable indicators.

Following the methodology of (Chen & Biljecki, 2023), indicators were grouped into following categories listed in Table 2.

Segmentation-based metrics indicate the probability of encountering specific objects categorized within an indicator (e.g., human, dog, cat within Life & Animals). These probabilities are estimated by analyzing the coverage of these objects relative to the entire image size. For detection-based indicators, SVIs without any signs of vandalism receive a score of 1, while those with evidence of vandalism are assigned 0. A normalized value between 0 and 1 is calculated for the "Number of Users"' category based on the minimum and maximum number of detected people observed in the area of interest. The scores for both analytical metrics (SVI and Colorfulness) are determined using the formulae outlined by Chen and Biljecki (2023). Finally, averaged indicators are obtained by averaging the scores across all regions on the map.

The majority of indicators belong to the segmentation-based category. Calculating their values required identifying various segments in the photos, such as sidewalks or greenery, and determining what percentage of the image each segment occupied. This process, known as semantic segmentation, was performed using the pre-trained DeepLabv3 model (Chen et al., 2017) using ResNet-269 network (Zhang et al., 2022), trained on the ADE20K dataset (Zhou et al., 2017). Detection-based indicators primarily involved identifying the presence of people and animals in the photos. This task was handled using pre-trained Faster RCNN model (Ren et al., 2016) with a ResNet-269 backbone, trained on the MS COCO dataset (Lin et al., 2014). Only detections with

Table 1
Key urban amenities evaluated in proximity assessment of present article.

Number	Urban amenity layer	QuickOSM keys
1	Grocery retail	Supermarket, Convenience, Bakery
2	Educational facilities	School
3	Food services	Café, Restaurant
4	Health and well-being services	Clinic, Doctors, Veterinary
5	Religious and worship services	Places of worship
6	Recreational spaces	Garden, Park, Grass-land use, Recreational-land use
7	Cultural and artistic venues	Artwork, Museum, Cinema, Library
8	Public transportation	Tram and bus stops

Table 2
Categories of indicators used in urban space quality evaluation.

Group of indicators	Indicator name	Indicator type
Infrastructure and utilities	Lighting	Segmentation-based
	Signage & Emergency Items	Segmentation-based
	Seating	Segmentation-based
	Fences	Segmentation-based
	Sidewalk	Segmentation-based
	Dustbins	Segmentation-based
Natural and green spaces	Water Bodies	Segmentation-based
	Life & Animals	Segmentation-based
	Green Coverage	Segmentation-based
Aesthetic and visual elements	SIDI	Segmentation-based / analytical
	Surrounding Buildings	Segmentation-based
	Colourfulness	Analytical
	Vandalism	Detection-based
Public spaces and identity	View to Landmark	Segmentation-based
	Number of Users	Detection-based
	Public Space Identity	Segmentation-based

[1] Data availability was checked in June 2024.

a probability of 0.5 or higher were considered correct for the calculation of detection-based metrics. This threshold was adopted after reviewing detection results and performing sensitivity analysis. Tasks involving deep neural networks were implemented using the GluonCV framework (Guo et al., 2020). Lastly, the visual indicators focused on colorfulness and the SIDI index were calculated using the NumPy library in Python.

Figs. 1 and 2 illustrate the automated methodology used to assess spatial quality indicators across the case study area through object detection and semantic segmentation applied to Street View Imagery (SVI). Semantic segmentation further categorizes image regions, providing insights into factors such as environmental quality, accessibility, and aesthetic appeal.

3.3. Environmental assessment: water retention and susceptibility to flooding

To assess environmental susceptibility to flooding within the study area, the UFRM model of the InVEST software was applied. The UFRM model is a static, raster-based hydraulic model designed to evaluate the flood mitigation function of urban landscapes by quantifying spatial variation in water retention capacity. Rather than simulating flood dynamics or estimating event probabilities, the model identifies locations where land surface characteristics limit stormwater infiltration, thereby revealing areas that are physically predisposed to surface water accumulation during intense rainfall events (Azadgar et al., 2024; Ogawa et al., 2023; Quagliolo et al., 2023; Li, Ji, Wang and Huang, 2023).

Water retention was modelled by integrating three primary datasets: land cover data from the Urban Atlas 2018 (European Environment Agency, 2021), soil hydraulic properties derived from the ESDAC 3D Soil Hydraulic Database (European Commission, Joint Research Centre (JRC), 2017; Tóth et al., 2017), and runoff parameters obtained from the NRCS TR-55 biophysical table (USDA NRCS, 1986). These inputs were combined through the Curve Number approach to estimate the proportion of rainfall that can be retained or infiltrated by each raster cell. The resulting output highlights pixels where infiltration capacity is low and excess runoff is likely to occur, indicating areas with higher susceptibility to flooding. This spatially explicit representation of limited water retention provides a consistent basis for identifying flood-prone areas and integrating environmental susceptibility into the subsequent

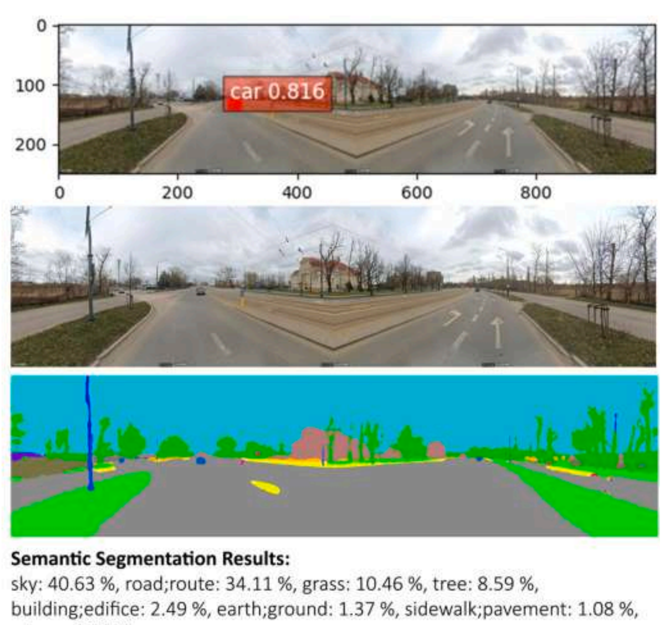

Fig. 1. Object detection and semantic segmentation applied on Street View Imagery with high spatial quality score.

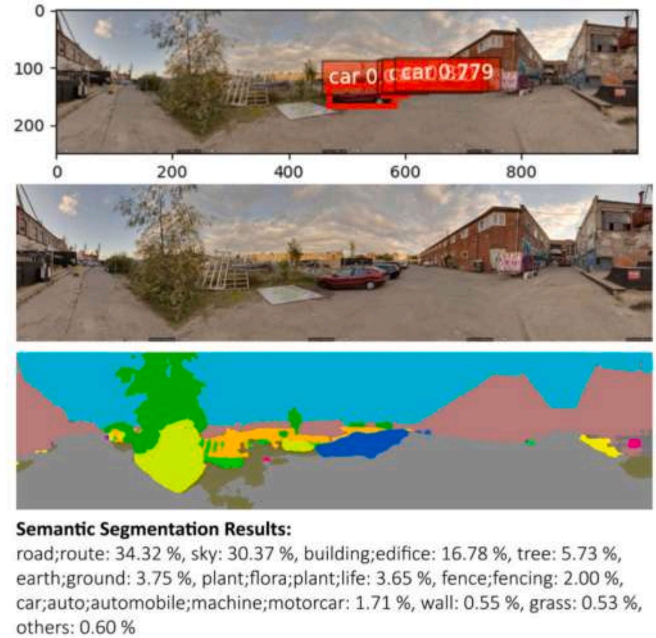

Fig. 2. Object detection and semantic segmentation applied on Street View Imagery with low spatial quality score.

spatial synthesis.

3.4. Spatial synthesis and hotspot identification

To integrate the results of the network analysis, public space quality evaluation, and environmental assessment, a threshold-based spatial synthesis was performed in QGIS. First, the output of the network analysis was reclassified into a binary accessibility selection layer, where areas lacking access to two or more amenity or public transport layers within the defined walking threshold were identified as accessibility-deficient, reflecting cumulative rather than isolated accessibility gaps. Second, public space quality results were converted into a binary layer by selecting areas with a spatial quality index of 0.3 or lower, corresponding to the lowest range of observed spatial quality conditions. Third, environmental susceptibility was represented by a binary layer identifying areas with water retention capacity values between 3 and 15, indicating limited infiltration potential and higher predisposition to surface runoff. These three binary selection layers were then spatially intersected to identify areas simultaneously meeting all criteria. The resulting intersection defines the final hotspot areas ($A \cap B \cap C$). The overall spatial selection and intersection workflow is schematically illustrated in Fig. 3.

3.5. Study area

To demonstrate the applicability of the proposed enhanced 15-min city (FMC) framework, a study area located north of Gdańsk's historic center was selected (Fig. 4). This area encompasses the former shipyard grounds, numerous industrial enterprises that historically supported shipyard operations, and residential neighborhoods developed in close proximity to these industrial zones. Such adjacent communities are often referred to as 'frontline' or 'fence-line' communities, as they are typically exposed to a range of environmental burdens—including noise, heavy traffic, unpleasant odors, and emissions from chemical and fossil fuel-based industries (Adams et al., 2018). Despite the presence of ambitious redevelopment programs targeting post-industrial areas, these surrounding neighborhoods are frequently overlooked. Urban revitalization efforts have historically prioritized economic growth, often at the expense of addressing the needs and well-being of nearby

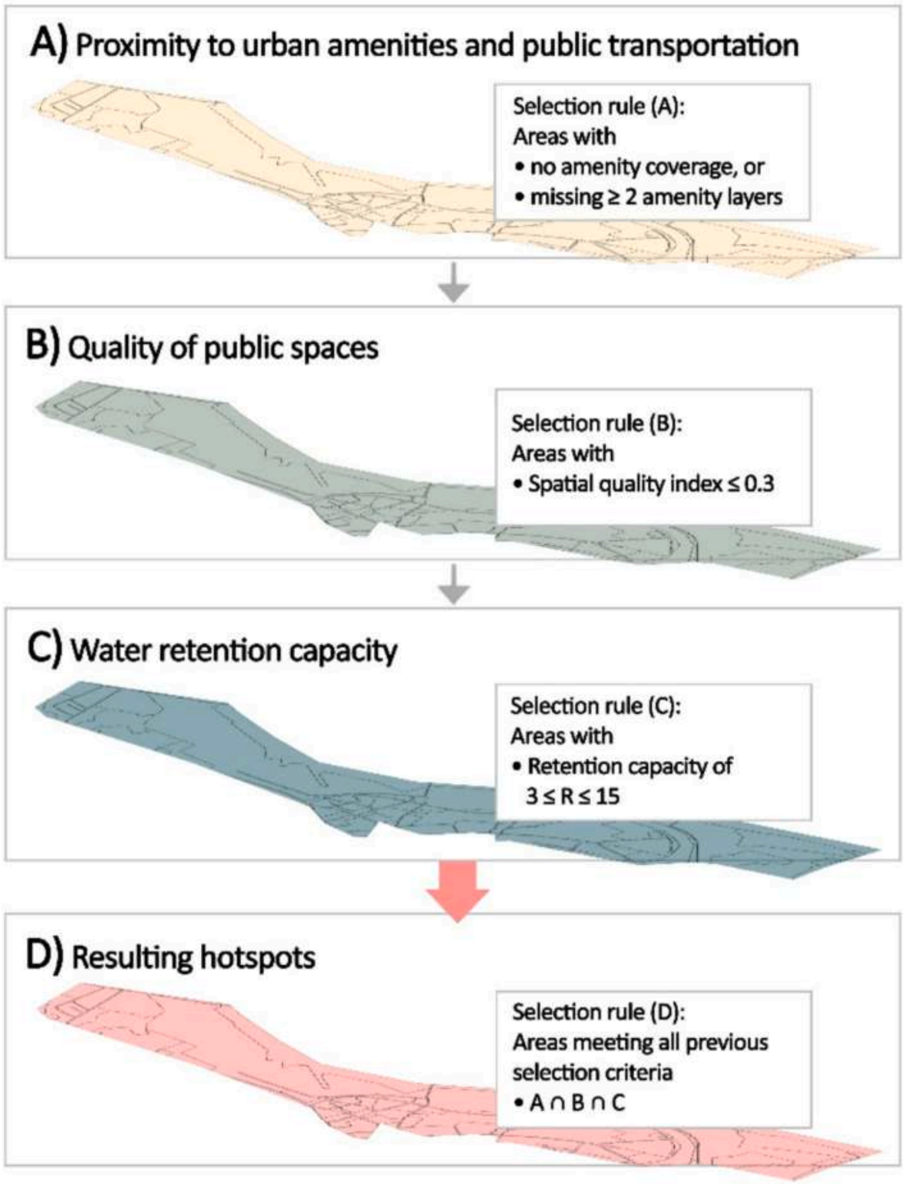

Fig. 3. Schematic illustration of the threshold-based spatial selection and intersection workflow used to identify priority areas.

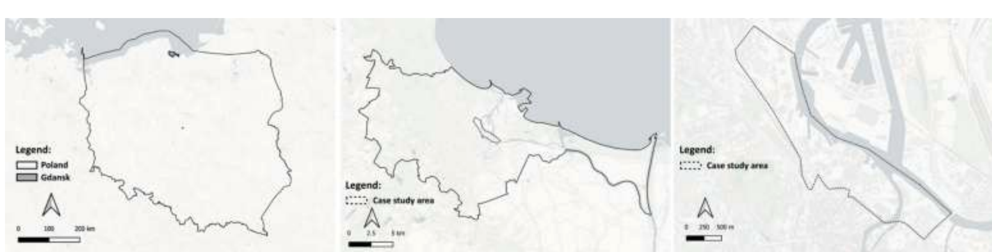

Fig. 4. Geographical context. From left to right, Gdańsk in Poland, the shipyard area in Gdańsk, and a zoomed-in view of the post-shipyard area and its vicinities.

communities, including former fence-line residents (Marchiel, 2024). In Gdańsk, the central part of the study area (Fig. 5), encompassing the core of the historic shipyard, is currently undergoing major investment and redevelopment.

The area's history dates back to the medieval period, when the original port and trade settlement, known as the Young City (Jungstadt), was first established (Samól, 2018). In the mid-19th century, the Prussian government designated the site for a naval base, which later evolved into the Imperial Shipyard (Kaiserliche Werft) after 1871. Over time, the surrounding areas were also developed for industrial and shipbuilding purposes, resulting in the emergence of an extensive maritime industrial zone (Lorens & Bugalski, 2021). Despite its proximity to Gdańsk's historic city center, this industrial district remained physically and functionally isolated for decades. This situation persisted until the late 20th century, when economic restructuring and the closure of the Gdańsk Shipyard led to its reclassification as part of the expanding

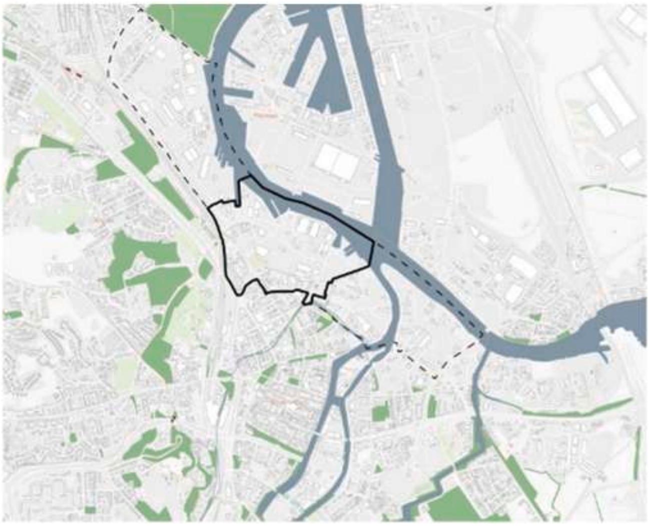

Fig. 5. The main investment zone on a background of the whole study area.

city center (Lipiński & Lorens, 2016). Numerous transformation strategies were subsequently developed, including the renewal of the most historically significant parts of the site (Lorens, 2019).

As a result of these transitions, the Young City, particularly its core area (the former Imperial Shipyard), was integrated into the broader Gdańsk City Centre. The adoption of a Local Development Plan in 2004 enabled the site's redevelopment for commercial and residential use, including the provision of transport and public space infrastructure. This marked the beginning of its incorporation into the civic fabric of the city. Since then, many new developments have been completed, including public institutions like the European Solidarity Center, large mixed-use complexes with substantial housing components, and commercial facilities such as food halls and hotels. Numerous additional projects are planned in the coming years.

Despite visible progress, public spaces and green infrastructure remain limited, predominantly confined to areas immediately surrounding new developments, and lacking integration into a cohesive, city-wide network. The Gdańsk Green Policy document has identified the entire area as suffering from a significant deficiency in greenery. Additionally, the area faces substantial flooding challenges due to heavy rains, high groundwater levels, and its low-lying topography, with public space continuities often disrupted and the waterfront largely inaccessible. Furthermore, while investment efforts have primarily concentrated on new residential and commercial projects, the adjacent fence-line neighborhoods, which are historically marginalized, appear to be overlooked, despite their need to benefit from the ongoing urban transformation. In recognition of these complex challenges of urban transformation, the entire Young City area and its surrounding neighborhoods were designated in 2023 as an Urban Living Lab (ULL) to implement the 15-min city (FMC) concept, under the European Driving Urban Transitions program, ENACT 15mC.

4. Results

4.1. Proximity to urban amenities and public transportation

The spatial analysis of proximity to urban amenities within the study area as demonstrated in Fig. 6, highlights a varied accessibility landscape across different sectors. The maps demonstrate that educational facilities, grocery retail and food related services are broadly distributed; ensuring essential services are within a 15-min walking distance along the street network for the majority of residents with only some relative spots that lack coverage. However, the coverage of recreational spaces, as well as religious services, shows a concentration in specific areas, which may suggest a gap in service accessibility specifically for northern and southern zones. Cultural and artistic venues, which also display an uneven distribution, potentially impact cultural engagement and recreational opportunities for residents outside the central areas.

The public transportation map showcased in Fig. 6 details proximity to public transportation stops underscoring the distribution and accessibility of transit services throughout the study area. Public transportation stops, marked by purple dots, are predominantly concentrated along major thoroughfares and densely populated sectors, providing essential connectivity for a large portion of the urban population. The shaded areas represent the coverage of public transportation, indicating where residents have easier access to transit options. Notably, while central areas show a dense network of stops, suggesting robust transit support, the peripheral zones appear less served, which could impact residents' ease of access to employment, education, and other services. This could be due to these underserved parts being on the riverside, thus providing fewer connecting points to the other side of the river, which can impact this section's coverage. This spatial arrangement calls for targeted improvements in public transportation infrastructure to ensure equitable access across all regions, potentially enhancing overall urban mobility and reducing reliance on private vehicle use.

The composite overlap map of amenity proximities within the study area presented in Fig. 7, provides a comprehensive view of accessibility to urban services. This map, which layers the proximity scores from various amenities, reveals a gradient from high to low accessibility, with the deepest orange areas indicating the highest concentration of accessible amenities. These zones, predominantly centralized, benefit from a synergy of services including educational, health, cultural, and retail amenities, which likely enhances the attractiveness and livability of these sectors. In contrast, areas with lighter shades exhibit significantly fewer amenities, indicating potential service deserts where residents might experience reduced quality of urban life and accessibility. This disparity in amenity distribution underscores the critical need for targeted urban development policies that focus on enhancing service accessibility in under-served areas, promoting a more balanced urban growth and ensuring equitable access to essential services for all residents.

4.2. Public space quality assessment

4.2.1. Infrastructure and utilities

The network of maps presented in the infrastructure and utilities category illustrates key spatial distributions of several public services and features within the study area. The maps in Fig. 8 highlight the coverage of dust bins, signage and emergency items, sidewalks, seating, fences, and lighting. Each map shows a heat map representation of the availability and density of these amenities, with higher scores represented by warm colors (yellow/orange) and lower scores by cooler tones (purple/blue). Dust bins are moderately distributed, with notable gaps in the southern region, while signage and emergency items have a more even and comprehensive spread, particularly in the central and northern parts. Sidewalks are less consistently represented, showing clusters of coverage but also indicating incomplete pedestrian infrastructure. Seating is sparse, suggesting a lack of comfort amenities for users across much of the area. Lighting shows strong coverage in central and southern zones, supporting safety, though gaps may exist elsewhere. Overall, the maps reveal both well-serviced areas and opportunities for improvement in public infrastructure.

4.2.2. Natural and green spaces

The series of maps presented in Fig. 9 show the spatial distribution of environmental attributes within the case study area, specifically focusing on water bodies, biodiversity, and green coverage. The first map illustrates the scattered presence of water bodies, marked by higher scores primarily along the river's trajectory, suggesting a linear distribution that potentially influences nearby ecological dynamics. The

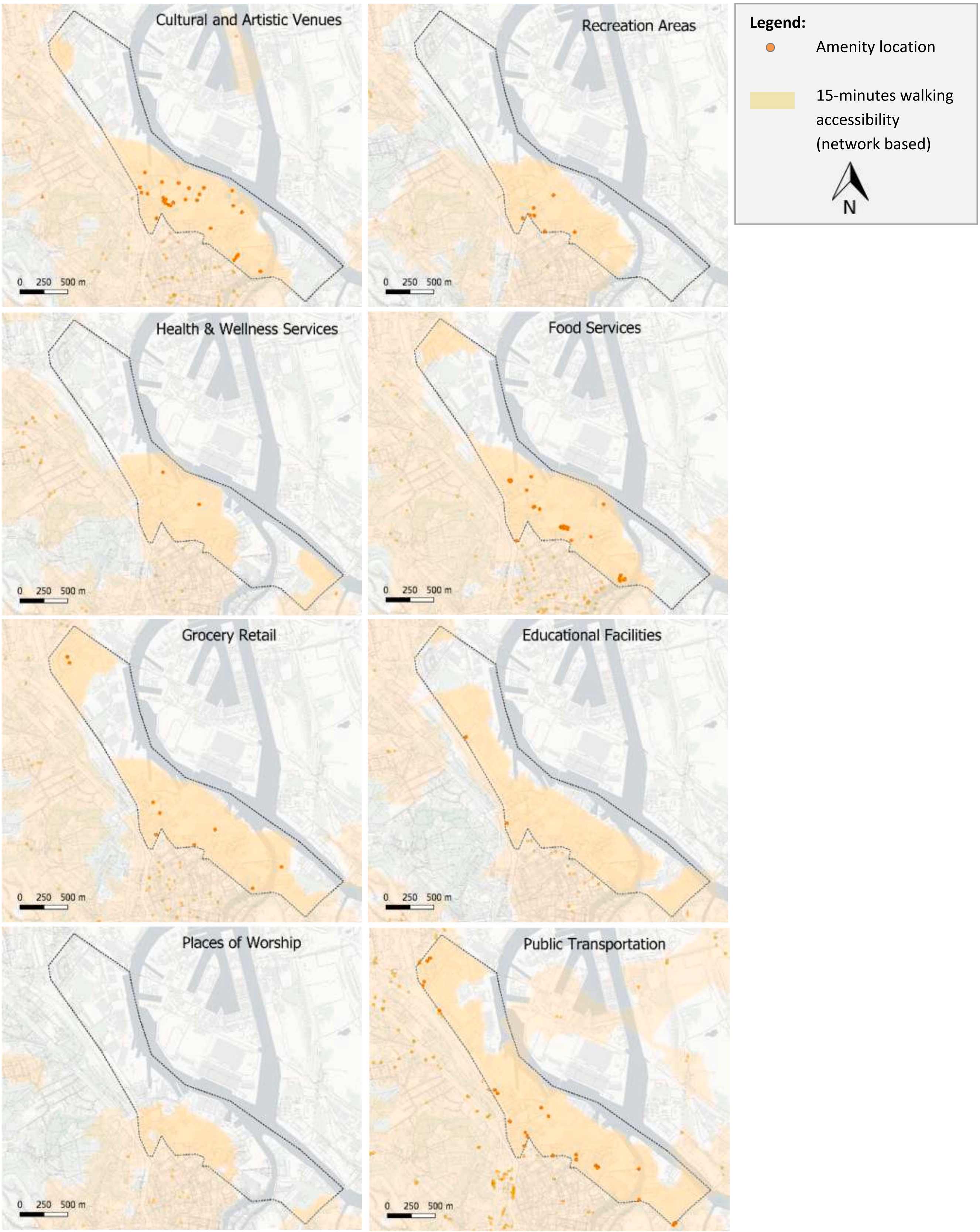

Fig. 6. Network-based accessibility coverage for individual amenity and public transport categories within the study area. Shaded yellow areas indicate locations reachable within a 15-min walking threshold (738 m network distance at 0.82 m/s), calculated using shortest-path analysis along the street network. Points represent amenity locations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

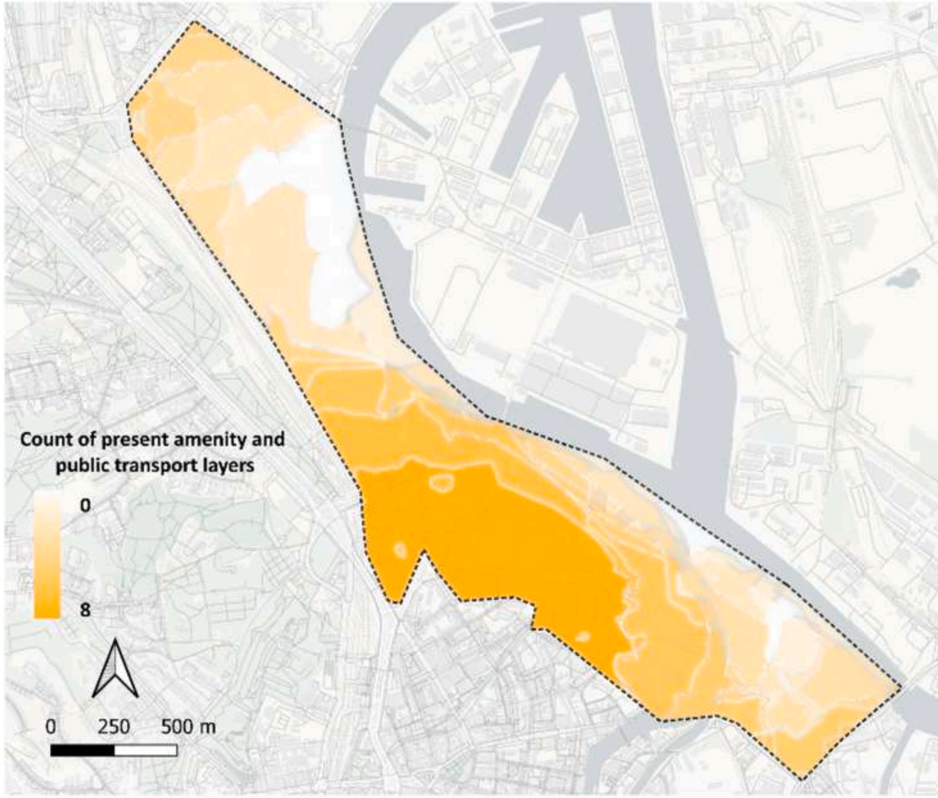

Fig. 7. Overlay of amenity and public transportation proximities in the case study area, indicating areas with high access to multiple services.

second map highlights areas with life and animal presence, which can only be observed in a small southern section of the study area. Conversely, the third map, detailing green coverage, shows a more dispersed and dense pattern across the area, with the highest concentrations in central and southern parts. This dispersion suggests that green areas are not solely dependent on immediate water body proximity, highlighting a varied urban ecological structure.

4.2.3. Aesthetic and visual elements

Further exploration of spatial characteristics within the case study area is depicted in Fig. 10, focusing on colorfulness, the impact of surrounding buildings, the Simpson's Diversity Index (SIDI) for visual features, and vandalism. The colorfulness map reveals vibrant zones predominantly concentrated along central regions, suggesting areas of high visual engagement which may correlate with active social spaces. The surrounding buildings map, with moderate to high scores across the area, points to a densely built environment that could influence both ecological and social dynamics. SIDI, assessing the diversity of visual features, indicates regions where visual elements are both rich and evenly distributed, aligning largely with vibrant and densely constructed areas, underscoring a dynamic interplay between urban form and visual diversity. Lastly, the vandalism map indicates specific hotspots that interestingly align with lower scores in both colorfulness and SIDI, possibly reflecting underutilized or neglected urban spaces.

4.2.4. Public spaces and identity

Fig. 11 illustrates the spatial distribution of views to landmarks, the identity of public spaces, and the number of users within the study area. The first map, showing views to landmarks, indicates concentrated areas where landmarks are highly visible, primarily along the central and southern half of the study area, enhancing the visual connectivity and attraction of these routes. The second map, focusing on public space identity, reveals that certain zones possess a strong, distinct identity, suggesting effective use of design or historical significance which likely contributes to their unique character and use. Lastly, the "Number of Users" map shows high user density in regions with extensive views to landmarks and strong public space identity, indicating a correlation between the attractiveness of visual and cultural features and the frequency of space usage. This suggests that areas which visually engage and offer distinct identities tend to draw more visitors.

4.2.5. Overall spatial quality of public spaces

The composite map in Fig. 12 synthesizes the average scores previously evaluated spatial quality indicators. This aggregation highlights areas with overall high scores, indicating zones of high urban quality that successfully integrate both functional and aesthetic elements. These areas are characterized by a rich interplay of accessibility, aesthetic appeal, and utility, drawing higher numbers of users and providing enhanced experiences mostly located in central and southern half of the case study area. Areas with lower average scores may indicate regions lacking in certain aspects, which could be targets for future urban improvement and development initiatives, specifically in the northern parts.

As a follow-up to the previous map, Fig. 13 provides a more granulated view using a Voronoi diagram. This approach further refines our understanding of spatial quality distribution, allowing for targeted urban enhancements. Each patch's color reflects its average quality score, ranging from lighter shades indicating lower qualities to deeper reds for higher qualities. The intense red patches, mostly in central and southern areas, denote superior spatial conditions benefiting from better environmental, infrastructural, and social attributes. Lighter areas suggest in contrast represent areas with lower spatial quality. This visual partitioning offers a more clear guidance for focused development and policy efforts.

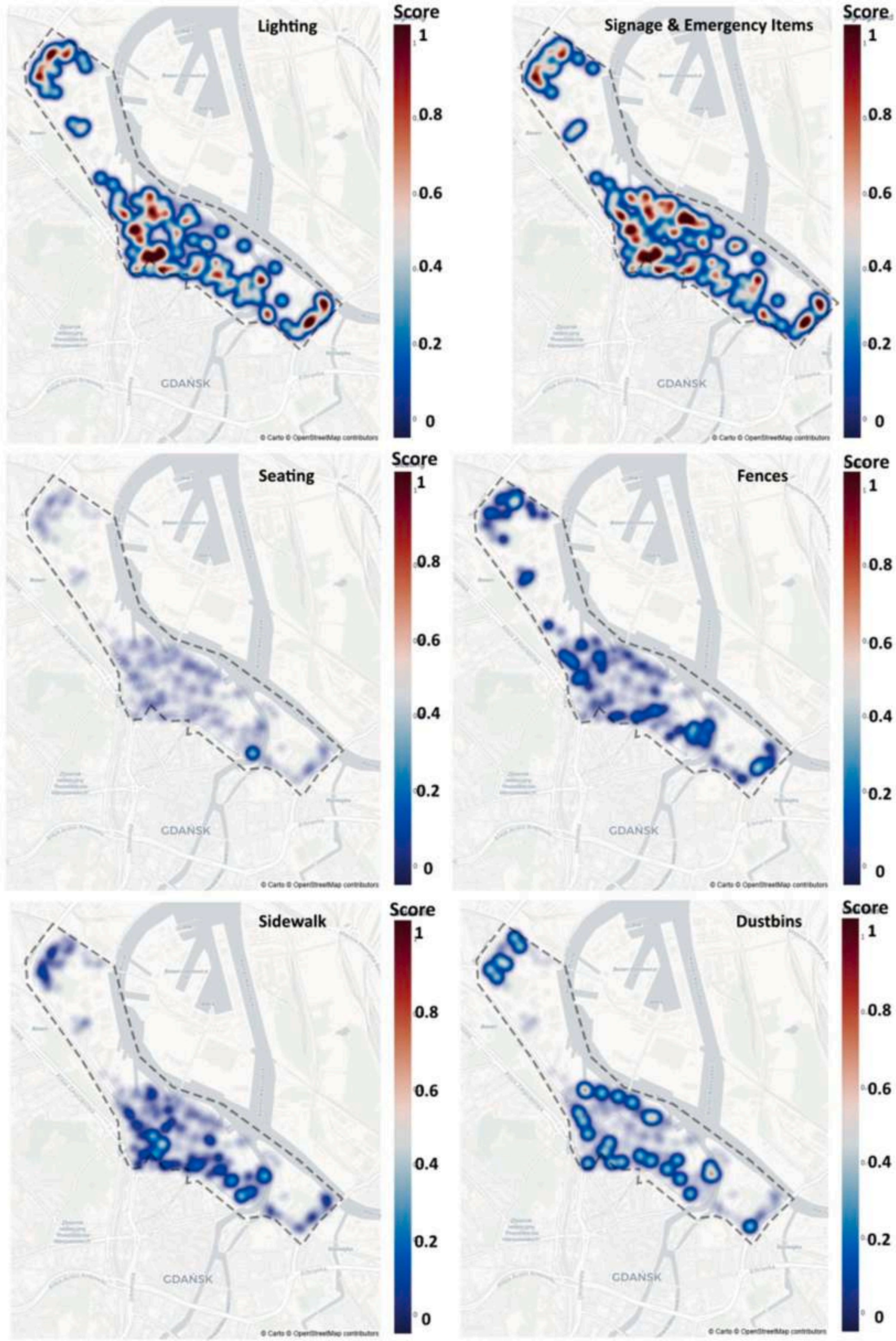

Fig. 8. Heat map of public space infrastructure quality in the case study area.

4.3. Environmental flood susceptibility assessment based on water retention capacity

To understand the hydrological situation of the study area, Fig. 14 displays spatial variations in water retention levels across the whole city of Gdańsk, with values ranging from 3.5 to 30.6 m^3. Areas with higher water retention capacity are represented in dark purple, blue and blue-green shades, while lower retention areas appear in yellow and light green.

In the case study area, outlined in white, water retention levels exhibit distinct spatial patterns. The highest retention levels, indicated by shades of blue-green and blue, are primarily concentrated in the

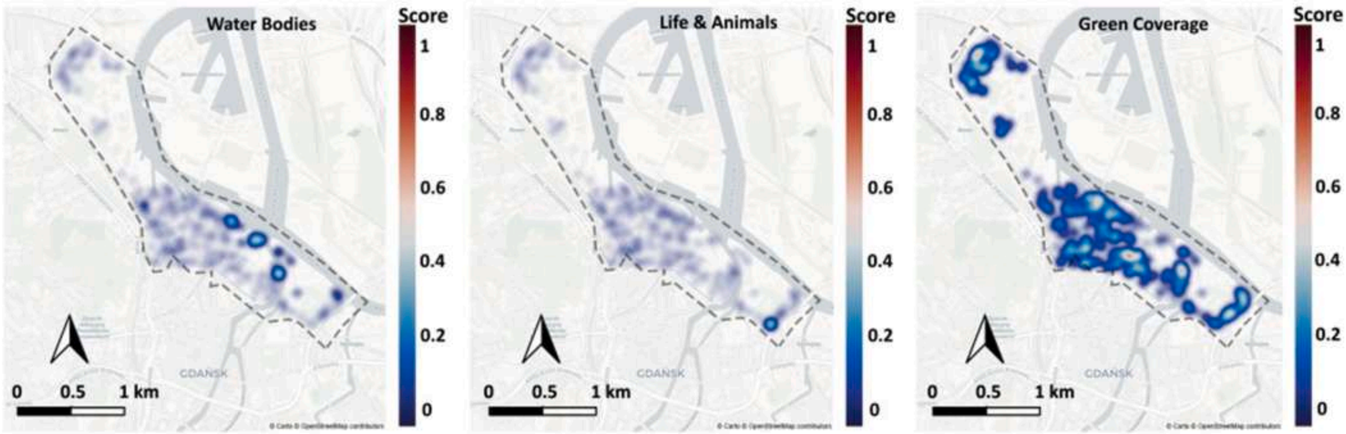

Fig. 9. Heat map of public spaces' natural and greenery quality in the case study area.

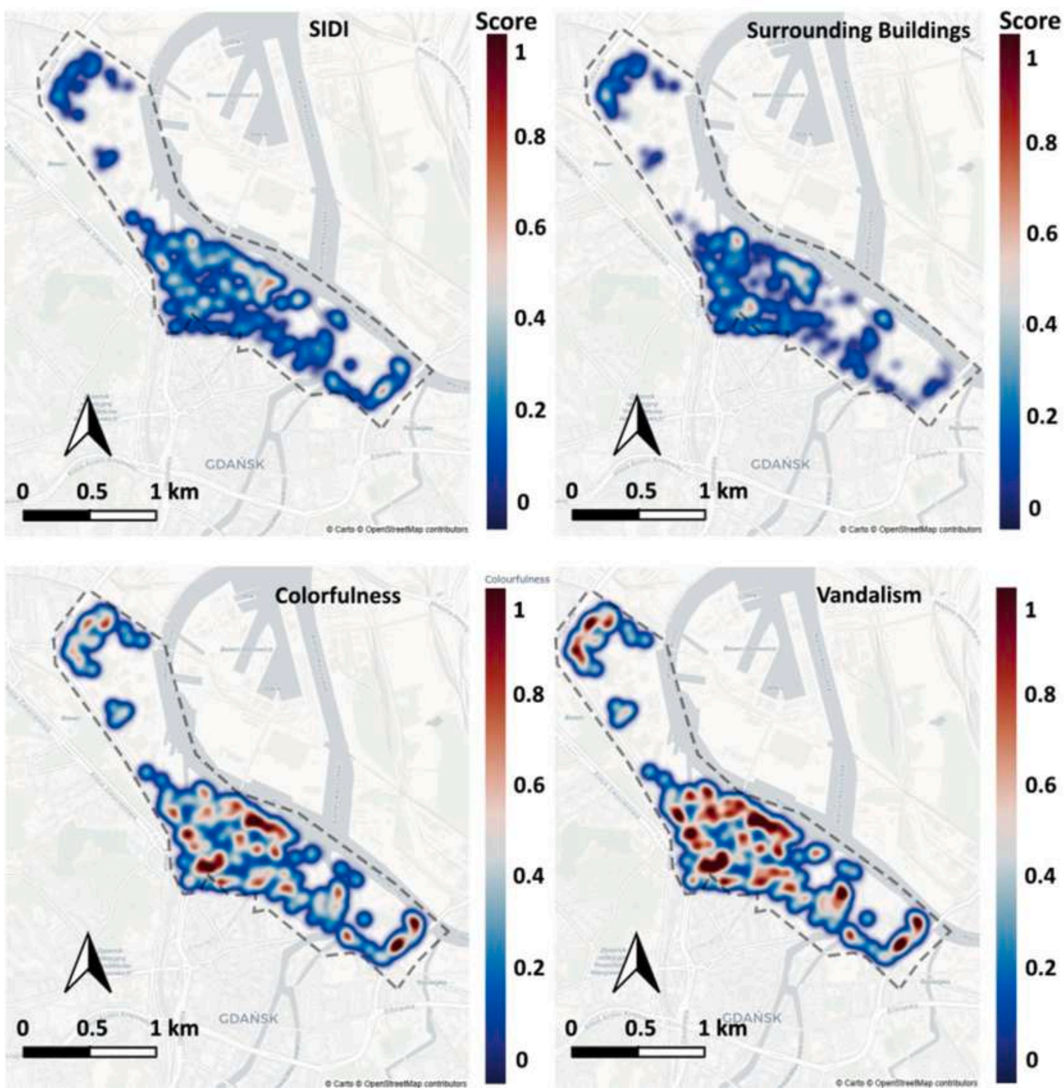

Fig. 10. Heat map of public spaces' aesthetic and visual elements quality in the case study area.

northern and central portions of the outlined region, suggesting that these areas likely have more permeable surfaces or natural features that facilitate water absorption and storage. In contrast, the lower retention areas, marked by yellow and light green hues, are generally found along the boundaries and in more densely urbanized sections, where impermeable surfaces limit water infiltration. This spatial differentiation within the case study area highlights variations in land use and surface types, which significantly impact the area's ability to retain water.

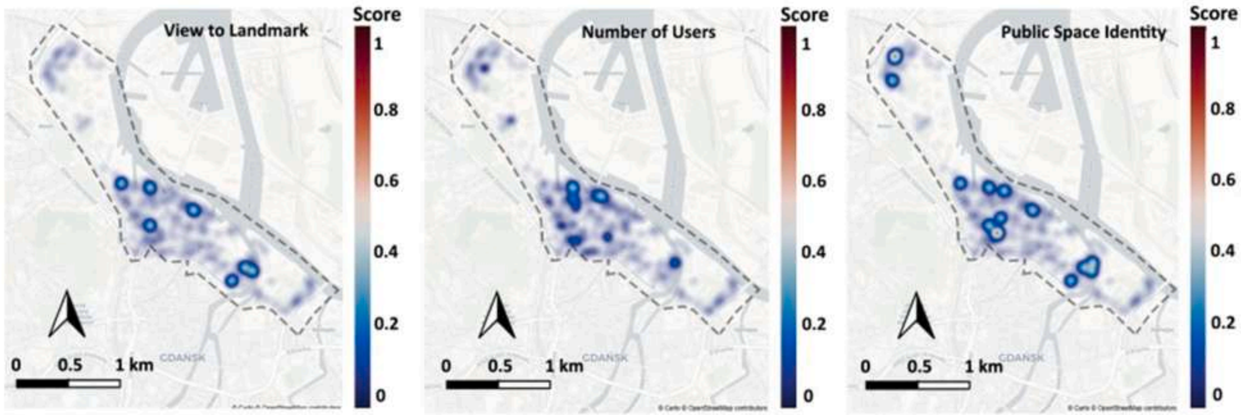

Fig. 11. Heat map of public space identity in the case study area.

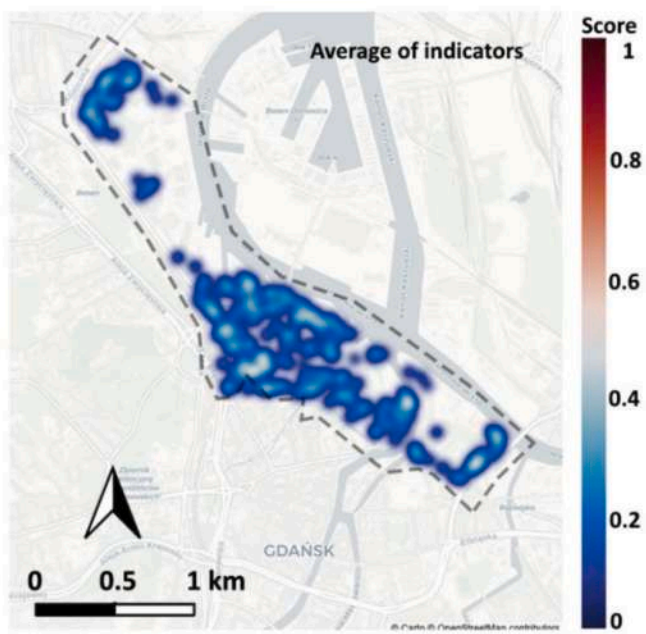

Fig. 12. Heat map showcasing the average of spatial quality indicators in case study area.

This static representation of water retention capacity serves as a proxy for flood susceptibility. Areas characterized by lower retention capacity are more likely to be unable to absorb excess runoff during intense rainfall events, leading to surface water accumulation. Such conditions can disrupt the continuity and usability of public spaces, particularly for pedestrians and cyclists, and may ultimately reduce effective walking accessibility within the study area. The observed spatial differentiation therefore highlights not only hydrological vulnerability but also its potential implications for everyday urban mobility.

4.4. Identifying areas in urgent need of intervention

Figs. 15 and 16 methodically layer spatial quality, water retention capacity, public transportation, and amenity coverage to evaluate the study area within the 15-min city framework. This integration effectively identifies critical "areas of concern," predominantly concentrated in the southeastern and northern parts of the study area, beyond the central part of the study area, as highlighted also in red on Fig. 16. These marked zones signal where significant urban development interventions are urgently needed to meet the ideals of the FMC model, especially in terms of environmental resilience, proximity of urban amenities, and the quality of public spaces. The red areas primarily located along the southeastern waterfront and the northern sectors of the study area demonstrate severe deficits in key factors. Notably, most of these hotspots correspond to former fence-line neighborhoods positioned to the south and north of the central redevelopment zone.

5. Discussion

Implementing the proposed 15-min city (FMC) framework in Gdańsk's post-industrial areas highlights the multifaceted challenges and opportunities in transforming urban districts into sustainable, accessible, and vibrant neighborhoods. This study demonstrates how leveraging advanced methodologies - including Street View Imagery (SVI), computer vision, AI tools, and environmental modeling – can provide nuanced insights into spatial quality, environmental resilience, and proximity to urban amenities, including access to public transportation in a synergic way. The digital diagnostics approach, particularly our multi-criteria hotspot mapping, is designed precisely to identify areas where these dimensions intersect and reveal compounded deficits, thereby offering an actionable tool for urban planning that goes beyond simply acknowledging previously neglected aspects.

The findings underscore the importance of multi-criteria analysis in identifying areas requiring targeted interventions to align with FMC principles. Unlike conventional approaches focusing mainly on proximity metrics, this study integrates diverse indicators—such as public space quality, flood risk, and amenity accessibility – to foster a nuanced understanding of urban deficiencies. For example, spatial quality assessments in our case study revealed fragmented pedestrian infrastructure along the waterfront, characterized by sparse sidewalks, limited seating, inadequate lighting, and low levels of public activity. These deficiencies contrast sharply with Gdańsk's vision of transforming its waterfront into an attractive FMC district, underscoring that effective FMC implementation demands attention to the qualitative experience of urban spaces, not just their quantitative accessibility (Dal Cin, Hooimeijer and Silva, 2021).

By enabling detailed analysis of individual layers – each highlighting deficiencies based on specific indicators – the methodology fosters context-sensitive solutions that account for local urban strategies, environmental factors, and socio-cultural contexts. This layered approach avoids prescriptive solutions and instead promotes adaptive governance models that reflect the unique needs of each neighborhood. For instance, addressing issues identified in one layer (e.g. reduced water retention capacity that increases the risk of flash-floods) can be complemented by improvements in other areas (e.g., green infrastructure), creating integrated solutions that enhance public space quality,

Fig. 13. Average score of spatial displayed quality using Voronoi diagram.

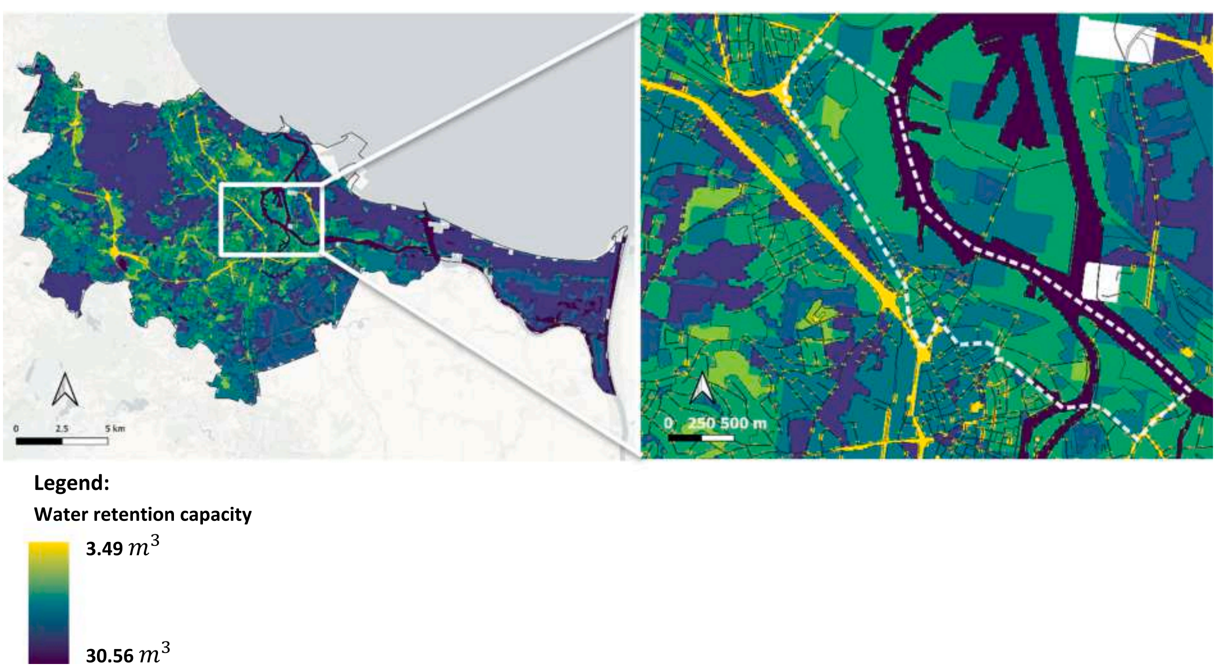

Fig. 14. Water retention capacity in Gdansk and in the case study area.

public health and resilience. This is particularly important as it addresses key critiques of physical determinism associated with the 15-min city concept, a challenge that arises when focusing narrowly on a single factor or a small group of selected factors (Khavarian-Garmsir et al., 2023; Mouratidis, 2024). Although demonstrated in the post-industrial waterfront areas of Gdańsk, the proposed framework is adaptable to diverse urban typologies, making it relevant for broader contexts. The core principles of integrating multi-dimensional assessments are universally applicable, allowing for local adaptation of indicators and data sources to reflect specific urban realities and challenges, whether landlocked or coastal.

Environmental resilience is a critical yet underexplored dimension of

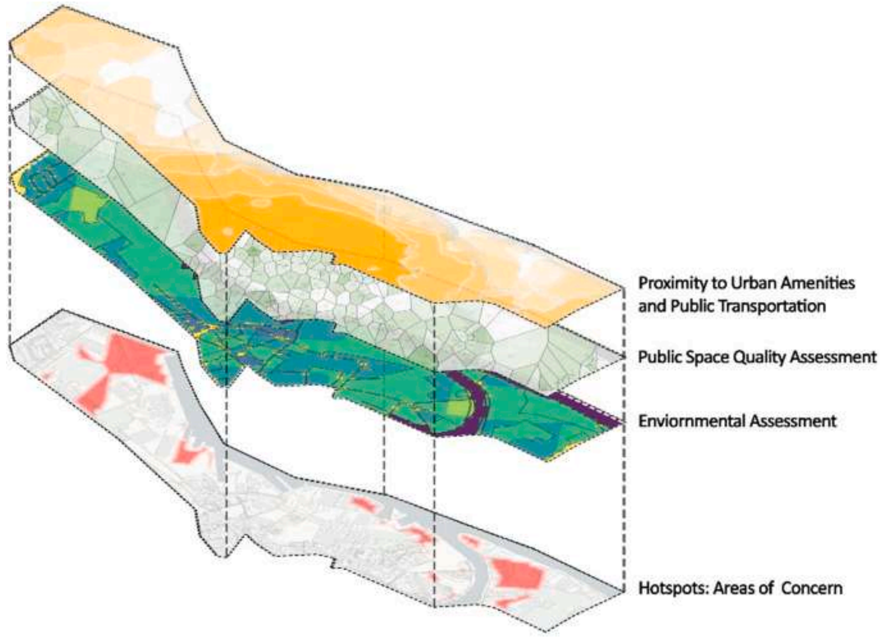

Fig. 15. Layered analysis of spatial quality, water retention capacity, public transportation proximity, and amenity coverage with identified areas of concern.

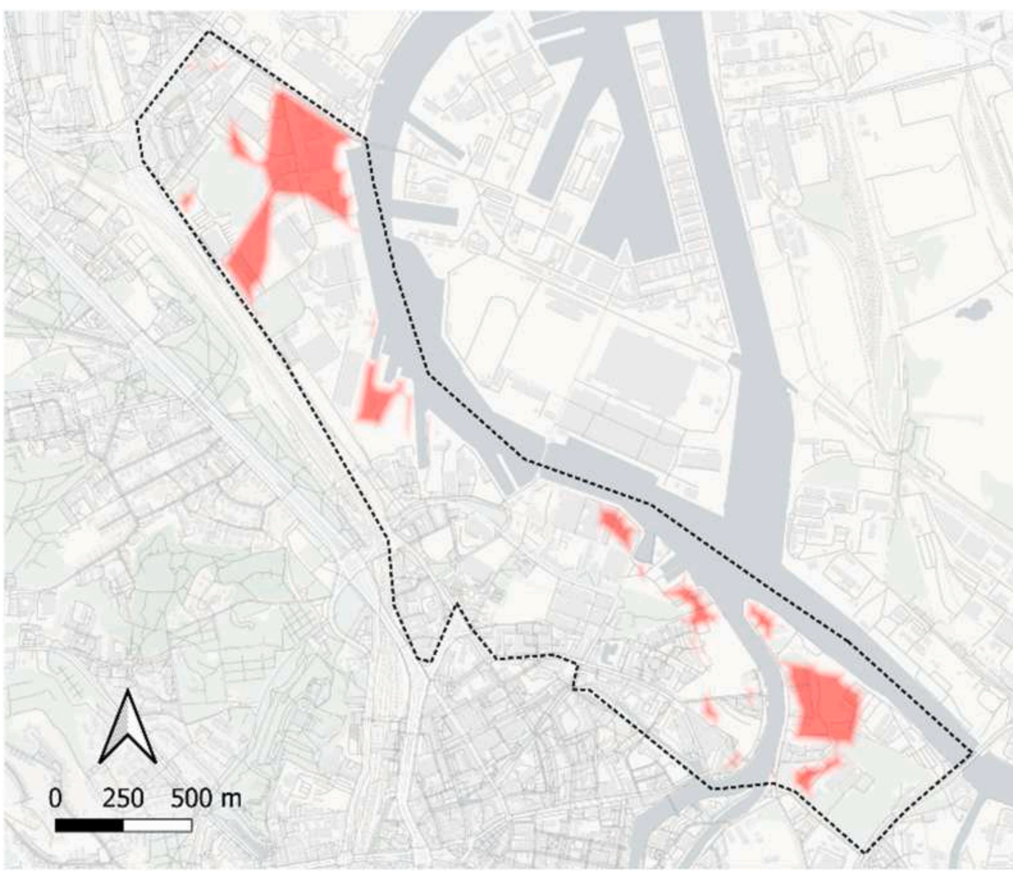

Fig. 16. Map of identified areas of concern within the case study area.

the FMC framework. While many studies emphasize the model's role in reducing carbon footprints through proximity-based planning (Allam et al., 2022a; Moreno et al., 2021), few address its capacity to mitigate localized climate risks such as flooding or heatwaves. This study directly bridges this gap by incorporating flood risk assessments using the InVEST's UFRM model. In our case study, results reveal that water retention capacity across much of the study area is low or very low, often overlapping with underserved neighborhoods. Heavy rainfall exacerbates mobility barriers for residents, effectively negating FMC accessibility claims. Nature-based solutions such as bioswales, rain gardens, retention ponds, and green pathways offer dual benefits: enhancing water retention capacity while improving public space quality and aesthetic appeal. These interventions strengthen urban resilience while aligning with FMC principles of sustainability and livability. For example, Copenhagen's cloudburst plan demonstrates how integrating green corridors can simultaneously reduce flood risks and increase pedestrian activity by creating multifunctional spaces for ecological and social purposes (Leonardsen, 2025). In Gdańsk's case, hotspots identified on final maps could be reconsidered from this perspective to unlock opportunities for integrated solutions that address both environmental performance, human well-being and accessibility. Notably, while our environmental considerations primarily focus on flooding, which is a predominant issue in Gdańsk, the framework's adaptable nature allows for these assessments to be replaced by other environmental concerns relevant to other specific case studies.

This finding underscores a critical equity dimension in urban redevelopment: the areas identified as most deficient in spatial quality, environmental resilience, and access to urban amenities, as marked on Figs. 15 and 16, correspond predominantly to former fence-line communities. These neighborhoods, historically situated on the periphery of industrial zones, often developed as company settlements, have been disproportionately exposed to environmental stressors while receiving limited infrastructural investment. The fact that they continue to lag behind, even as central areas undergo substantial transformation, highlights the risk of repeating patterns of exclusion within contemporary urban planning. This is strengthened by the fact that these areas are not subject to redevelopment, as no new projects are located directly within these areas, but rather within sites located in the designated transformation areas. Therefore, they rather serve as "border zones" between the "old" and "new" neighborhoods. At the same time spatial planning – due to its character – provides vision of future/ultimate state of the area, without any differentiation to the previous character of the particular sites and their origin. This comes from the fact that current Polish planning system does not include any "action planning" based instruments, but rather the "regulatory ones" only. Therefore, dealing with this topic requires not only understanding of the different character of these areas, but also inventing the new planning instruments.

While this finding highlights the limitations of current planning tools, addressing these disparities is essential not only to fulfill the inclusive vision of the 15-min city framework but also to ensure that urban regeneration delivers equitable outcomes. Prioritizing interventions in these underserved zones can help correct historical imbalances, integrate marginalized communities into the fabric of the evolving city, and create more socially and environmentally just urban environments (Sepe, 2023). Interestingly, some hotspots correspond also to new residential developments, demonstrating financial gain over the space quality and environmental considerations. As seen in forward-looking initiatives like the Westport Waterfront project in Baltimore, equitable regeneration requires not only physical redevelopment but also economic and social integration (Zhang, 2022). Another key issue is the risk of gentrification and social inequality, where more accessible neighborhoods may see rising property values, potentially displacing lower-income residents (Elldér, 2024; Guzman et al., 2024). This calls for a shift in policy focus toward more holistic and community-centered approaches to urban regeneration within FMC framework.

The automated methodology employed in this study represents a significant advancement over traditional fieldwork-based evaluations of public spaces. Using pre-trained deep learning models for semantic segmentation and object detection, spatial quality assessments were streamlined into efficient processes that can be repeated frequently to monitor changes over time. This scalable and time-efficient approach reduces reliance on manual methods and enables faster, large-scale evaluations. As such, it is particularly well-suited for assessing dynamically evolving urban transformations. Moreover, the accessibility of the methods and data tools used in this study makes the approach easily replicable. However, some limitations arise from reliance on GSV imagery, which is predominantly captured from roads and may not fully represent off-road spaces. Future research could integrate complementary data sources such as drone imagery or crowdsourced contributions to enhance comprehensiveness and accuracy. Expanding datasets to include non-road urban spaces, such as parks or pedestrian boulevards, would provide deeper insights into spatial dynamics while improving monitoring capabilities for rapidly transforming areas like Gdańsk's post-industrial district. Additionally, integrating real-time IoT sensors to monitor public space usage post-intervention could provide dynamic feedback for adaptive governance models. Performance metrics such as dwell time, user diversity, and ecological impact should be used to evaluate the success of these spaces over time.

For policymakers, this study highlights the need to embed space quality and environmental resilience metrics into FMC frameworks alongside traditional proximity indicators. Digital tools that enable rapid modeling can help cities integrate climate adaptation strategies into zoning policies while promoting livable urban spaces and inclusivity for marginalized groups. Locally, Gdańsk's designation as an Urban Living Lab (ULL) provides an opportunity to pilot participatory design processes that engage residents in co-creating solutions tailored to their needs. This emphasizes that while our framework provides a robust diagnostic tool, its application in any given city must be guided by explicit, context-specific policy goals to foster equity and integrate local knowledge. The framework does not propose a universal solution, but rather a flexible methodology to identify challenges and opportunities for intervention, tailored to local needs and existing governance structures.

6. Conclusion

This study introduces an enhanced 15-min city (FMC) framework, that advances existing principles through an integrated digital diagnostic approach to urban planning. By moving beyond solely proximity-based metrics, the framework evaluates urban areas using AI-driven tools and multi-criteria analysis, explicitly incorporating critical dimensions of spatial quality, environmental resilience and socio-spatial inclusivity. In doing so, it contributes directly to current debates on the evolving FMC concept and provides actionable insights for transforming selected urban areas into sustainable, vibrant, and resilient environments.

Our findings underscore the imperative of addressing these multiple dimensions simultaneously. The digital diagnostic approach offers a scalable and efficient methodology for identifying complex spatial deficiencies, most notably exemplified by the compelling finding that 'hotspots' requiring intervention frequently correspond to former fence-line neighborhoods. These areas combining inadequate public space quality with high climate vulnerability and limited amenity access, demonstrate the critical need for highly targeted, context-responsive interventions.

This research effectively equips urban planners and policymakers with a powerful tool to guide equitable urban transformation, fostering communities that align with sustainability goals. Ultimately, our methodology offers a pathway for cities worldwide to proactively adapt FMC neighborhoods to environmental uncertainty, strengthen values related to spatial identity, and enhance human well-being.

A key contribution of this study is its advancement of the FMC framework toward a more holistic and stratified approach. By shifting from proximity-centered policies to multi-objective regeneration initiatives at the district scale, the FMC can serve as an umbrella framework that integrates cross-sectoral policies and interventions. This perspective respond to critiques of physical determinism and emphasizes the importance of tailoring urban planning strategies to local needs and contexts. The multi-criteria analysis developed in this study illustrates how digital tools can support this process by identifying spatial deficiencies and guiding context-specific solutions, while reaffirming that, although common methodologies can be applied across different cities, every resulting project and policy should remain inherently place-based.

CRediT authorship contribution statement

Anahita Azadgar: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Marichela Sepe:** Writing – original draft, Conceptualization. **Artur Gańcza:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Conceptualization. **Piotr Lorens:** Writing – original draft. **Giulia Luciani:** Writing – review & editing, Writing – original draft. **Lucyna Nyka:** Writing – review & editing, Writing – original draft, Supervision, Investigation, Funding acquisition, Conceptualization.

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Declaration of interests

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Lucyna Nyka reports financial support and article publishing charges were provided by National Centre for Research and Development. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

Abdelkarim, S., Ahmad, A., Ferwati, S., & Naji, K. (2023). Urban facility management improving livability through smart public spaces in smart sustainable cities. *Sustainability*. https://doi.org/10.3390/su152316257

Adams, A. E., Shriver, T. E., Saville, A., & Webb, G. R. (2018). Forty years on the fenceline: Community, memory, and chronic contamination. *Environmental Sociology, 4*(2), 210–220. https://doi.org/10.1080/23251042.2017.1414660

Akrami, M., Sliwa, M. W., & Rynning, M. K. (2024). Walk further and access more! Exploring the 15-minute city concept in Oslo, Norway. *Journal of Urban Mobility, 5*, Article 100077.

Allam, Z., Bibri, S., Chabaud, D., & Moreno, C. (2022a). The theoretical, practical, and technological foundations of the 15-minute city model: Proximity and its environmental, Social and Economic Benefits for Sustainability. *Energies*. https://doi.org/10.3390/en15166042

Allam, Z., Bibri, S. E., Chabaud, D., & Moreno, C. (2022b). The '15-Minute City' concept can shape a net-zero urban future. *Humanities and Social Sciences Communications, 9* (1), 1–5.

Allam, Z., Khavarian-Garmsir, A. R., Lassaube, U., Chabaud, D., & Moreno, C. (2024). Mapping the implementation practices of the 15-minute city. *Smart Cities, 7*(4), 2094–2109. https://doi.org/10.3390/smartcities7040083

Almeida, M. J., & Fonseca, F. (2025). Proximity and active accessibility to urban green spaces in Porto through the lens of the 15-minute city. *Urban Science, 9*(11), 458. https://doi.org/10.3390/urbansci9110458

Azadgar, A., Luciani, J., & Nyka, L. (2025). Spatial allocation of nature-based solutions in the form of public green infrastructure in relation to the socio-economic district profile–a GIS-based comparative study of Gdańsk and Rome. *Land Use Policy, 150*, Article 107454. https://doi.org/10.1016/j.landusepol.2024.107454

Azadgar, A., Nyka, L., & Salata, S. (2024). Advancing urban flood resilience: A systematic review of an urban flood risk mitigation model, research trends, and future directions. *Land, 13*, 2138. https://doi.org/10.3390/land13122138

Badland, H., White, M., MacAulay, G., Eagleson, S., Mavoa, S., Pettit, C., & Giles-Corti, B. (2013). Using simple agent-based modeling to inform and enhance neighborhood walkability. *International journal of health geographics, 12*(1), 58. https://doi.org/10.1186/1476-072X-12-58.

Bajjali, W. (2023). Proximity and network analysis. In *ArcGIS Pro and ArcGIS Online: Applications in Water and Environmental Sciences* (pp. 287–331). Cham: Springer International Publishing.

Barbieri, L., D'Autilia, R., Marrone, P., & Montella, I. (2023). Graph representation of the 15-minute city: A comparison between Rome, London, and Paris. *Sustainability, 15* (4), 3772. https://doi.org/10.3390/su15043772

Barratt, P., & Swetnam, R. (2022). A civic and sustainable 15-minute campus? Universities should embrace the 15-minute city concept to help create vibrant sustainable communities. *Local Economy, 37*, 734–744. https://doi.org/10.1177/02690942231175096

Bertoni, A., Dubini, P., & Monti, A. (2021). Participatory event platforms in the urban context: The importance of stakeholders' meaning of "participation". In *Cultural initiatives for sustainable development: Management, participation and entrepreneurship in the cultural and creative sector* (pp. 271–292). Cham: Springer International Publishing.

Biljecki, F., & Ito, K. (2021). Street view imagery in urban analytics and gis: A review. *Landscape and Urban Planning, 215*, Article 104217. https://doi.org/10.1016/j.landurbplan. 2021.104217

Biraghi, C. A., Ogut, O., Dong, T., & Tadi, M. (2025). CityTime: A novel model to redefine the 15-minute city globally through urban diversity and proximity. *Urban Science, 9* (2), 36. https://doi.org/10.3390/urbansci9020036

Burda, I. M., & Nyka, L. (2023). Innovative urban blue space design in a changing climate: Transition models in the Baltic Sea region. *Water, 15*, Article 2826. https://doi.org/10.3390/w15152826

Chen, L. C., Papandreou, G., Schroff, F., & Adam, H. (2017). Rethinking atrous convolution for semantic image segmentation. arXiv. arXiv preprint arXiv: 1706.05587. *5*.

Chen, S., & Biljecki, F. (2023). Automatic assessment of public open spaces using street view imagery. *Cities, 137*, Article 104329.

Chen, X., & He, B.-J. (2022). Development of a framework for urban heat adaptation in 15-minute city. *IOP Conference Series: Earth and Environmental Science, 1122*(1), Article 012005. https://doi.org/10.1088/1755-1315/1122/1/012005

Cilliers, E. J., & Timmermans, W. (2016). Transforming spaces into lively public open places: Case studies of practical interventions. *Journal of Urban Design, 21*(6), 836–849. https://doi.org/10.1080/13574809.2016.1234336

Crappsley, R. (2017). Designing streets for good health: Now and in the future. *Urban Design Journal, 143*, 10–11.

Dal Cin, F., Hooimeijer, F., & Silva, M. M. (2021). Planning the urban waterfront transformation, from infrastructures to public space design in a sea-level rise scenario: The European Union prize for contemporary architecture case. *Water, 13* (2), 218. https://doi.org/10.3390/w13020218

Distefano, N., & Leonardi, S. (2023). Fostering urban walking: Strategies focused on pedestrian satisfaction. *Sustainability, 15*(24), Article 16649. https://doi.org/10.3390/su152416649

Elldér, E. (2024). Built environment and the evolution of the "15-minute city": A 25-year longitudinal study of 200 Swedish cities. *Cities, 149*, Article 104942.

Enwin, A., & Ikiriko, T. (2023). Balancing urban development: Literature on the nexus between affordable housing and urban sprawl. *International Journal of Research and Review.*. https://doi.org/10.52403/ijrr.20231259

European Commission, Joint Research Centre (JRC). (2017). *3D soil hydraulic database of Europe at 1 km and 250 m resolution*. European Commission. Joint Research Centre (JRC) [Dataset] PID: http://data.europa.eu/89h/jrc-esdac-108.

European Environment Agency. (2021). *Urban atlas land cover/land use 2018 (vector), Europe, 6-yearly, Jul. 2021* https://doi.org/10.2909/fb4dffa1-6ceb-4cc0-8372-1ed354c285e6

Evans, G. (2009). Accessibility, Urban Design and the Whole Journey Environment. *Built Environment (1978-), 35*(3), 366–385. http://www.jstor.org/stable/23289759.

Fan, T., & Chapman, A. (2024). Clarifying the levers of carbon emission reduction in compact cities in China: A multi-sectoral approach. *Sustainable Futures, 7*, Article 100200.

Ferrer-Ortiz, C., Marquet, O., Mojica, L., & Vich, G. (2022). Barcelona under the 15-minute city lens: Mapping the accessibility and proximity potential based on pedestrian travel times. *Smart Cities, 5*(1), 146–161.

García-Palomares, J., Ribeiro, J., Gutiérrez, J., & Marques, T. (2018). Analysing proximity to public transport: The role of street network design. *Boletín de la Asociación de Geógrafos Españoles*, 102–130. https://doi.org/10.21138/BAGE.2517

Gehl, J. (2011). *Life between buildings: Using public space*. Washington, D.C.: Island Press.

Genovese, D., Candiloro, S., D'Anna, A., Dettori, M., Restivo, V., Amodio, E., & Casuccio, A. (2023). Urban sprawl and health: A review of the scientific literature. *Environmental Research Letters, 18*. https://doi.org/10.1088/1748-9326/ace986

Giles-Corti, B., Foster, S., & Lowe, M. (2023). What are the lessons from COVID-19 for creating healthy, sustainable, resilient future cities? *npj Urban Sustainability, 3*, 23. https://doi.org/10.1038/s42949-023-00107-y

Graells-Garrido, E., Serra-Burriel, F., Rowe, F., Cucchietti, F. M., & Reyes, P. (2021). A city of cities: Measuring how 15-minutes urban accessibility shapes human mobility in Barcelona. *PLoS One, 16*(5), Article e0250080.

Guo, J., He, H., He, T., Lausen, L., Li, M., Lin, H., Shi, X., Wang, C., Xie, J., Zha, S., Zhang, A., Zhang, H., Zhang, Z., Zhang, Z., Zheng, S., & Zhu, Y. (2020). Gluoncv and gluonnlp: Deep learning in computer vision and natural language processing. *Journal of Machine Learning Research, 21*, 1–7. http://jmlr.org/papers/v21/19-429.html.

Guzman, L. A., Oviedo, D., & Cantillo-Garcia, V. A. (2024). Is proximity enough? A critical analysis of a 15-minute city considering individual perceptions. *Cities, 148*, Article 104882.

Han, J. (2020). Can urban sprawl be the cause of environmental deterioration? Based on the provincial panel data in China. *Environmental Research, 189*, Article 109954. https://doi.org/10.1016/j.envres.2020.109954

Hosford, K., Beairsto, J. A. B., & Winters, M. (2022). Is the 15-minute city within reach? Evaluating walking and cycling accessibility to grocery stores in Vancouver. *Transportation Research Interdisciplinary Perspectives, 14*(15), Article 100602.

Huang, W., & Khalil, E. B. (2023, June). Walkability optimization: Formulations, algorithms, and a case study of Toronto. In *, Vol. 37, No. 12. Proceedings of the AAAI Conference on Artificial Intelligence* (pp. 14249–14258).

Israel, F., Otero, G., Soza-Parra, J., & Broitman, D. (2026). (2026) 15-minute city, proximity, and urban segregation in Latin-American cities: The case of Santiago de Chile. *Transportation Research Part A: Policy and Practice, 204*, Article 104789.

Kaya, G. N., Beyhan, F., İlerisoy, Z. Y., & Cudzik, J. (2025). Evaluation of machine learning applications in building life cycle processes for energy efficiency: A systematic review. *Energy Reports, 13*, 4900–4916.

Kesarovski, T., & Hernández-Palacio, F. (2022). Time, the other dimension of urban form: Measuring the relationship between urban density and accessibility to grocery shops in the 10-minute city. *Environment and Planning B: Urban Analytics and City Science, 50*, 44–59. https://doi.org/10.1177/23998083221103259

Khavarian-Garmsir, A. R., Sharifi, A., & Sadeghi, A. (2023). The 15-minute city: Urban planning and design efforts toward creating sustainable neighborhoods. *Cities, 132*, Article 104101. https://doi.org/10.1016/j.cities.2022.104101

Kozar, L. J., Matusiak, M., & Bolimowski, S. (2024). 15-minute city: Identifying current and setting future research directions. *Scientific Papers of Silesian University of Technology, 197*, 387–405.

Kyriakidis, C., Apostolopoulos, K., Papadima, A., Sideris, A., & Potsiou, C. (2024). Navigating urban space. Tehnički. *Glasnik, 18*(4), 587–596. https://doi.org/10.31803/tg-20241013222733

Lee, D. (2022). *Public space in transition*. https://doi.org/10.1515/9783839462324

Azadgar, A., Gańcza, A., Asl, S. R., Salata, S., & Nyka, L. (2025). Optimizing nature-based solutions for urban flood risk mitigation: A multi-objective genetic algorithm approach in Gdańsk, Poland. *Science of the Total Environment, 963*, 178303.

Leonardsen, L. (2025). *Copenhagen cloudburst plan. Urban climate change research network*. Columbia University. https://doi.org/10.7916/82hd-8f49.

Li, Y., Ji, C., Wang, P., & Huang, L. (2023). Proactive intervention of green infrastructure on flood regulation and mitigation service based on landscape pattern. *Journal of Cleaner Production, 419*, Article 138152.

Lin, T. Y., Maire, M., Belongie, S., Hays, J., Perona, P., Ramanan, D., … Zitnick, C. L. (2014). *Microsoft coco: Common objects in context. In Computer Vision–ECCV 2014: 13th European Conference, Zurich, Switzerland, September 6–12, 2014, Proceedings, Part V 13 (pp. 740–755)*. Springer International Publishing.

Lipiński, J., & Lorens, P. (2016). *Młode Miasto Gdańsk. Laboratorium miejskich procesów rozwojowych* (pp. 1–352). Monoplan.

Liu, D., Kwan, M. P., & Wang, J. (2024). Developing the 15-Minute City: A comprehensive assessment of the status in Hong Kong. *Travel Behaviour and Society, 34*, Article 100666.

Lorens, P. (2019). Shaping the new face of the Imperial Shipyard in Gdańsk. *Przestrzeń i Forma, 40*, 151–170.

Lorens, P., & Bugalski, Ł. (2021). Reshaping the Gdańsk shipyard—The birthplace of the solidarity movement. The complexity of adaptive reuse in the heritage context. *Sustainability, 13*(13), 7183.

Magina, F. B., Paul, B. N., & Lupala, J. M. (2024). Impacts of urban sprawl on people's livelihoods: Analysis of urban fringe neighbourhoods in Dar Es Salaam, Tanzania. *International Planning Studies*, 1–15.

Marchiel, R. K. (2024). The paradox of urban revitalization: Progress and poverty in America's postindustrial era. *The Journal of American History, 111*(3), 613–614. https://doi.org/10.1093/jahist/jaae236

McCay, L. (2017). Designing mental health into cities. *Urban Design Journal, 142*, 25–27.

Moreno, C., Allam, Z., Chabaud, D., Gall, C., & Pratlong, F. (2021). Introducing the "15-Minute City": Sustainability, resilience and place identity in future post-pandemic cities. *Smart Cities, 4*, 93–111. https://doi.org/10.3390/smartcities4010006

Morganti, M., Mannucci, S., & Fiocchi, I. (2022). Pluvial flooding in compact neighbourhoods: Digital analysis for climate-adaptive buildings and urban spaces. In A. Rogora, & P. Carli (Eds.), *New energies for the cities* (pp. 31–52). UNA Press.

Mouratidis, K. (2024). Time to challenge the 15-minute city: Seven pitfalls for sustainability, equity, livability, and spatial analysis. *Cities, 153*, Article 105274.

Mun, H., Yeom, J., Oh, J., & Jung, J. (2025). Does a compact city really reduce consumption-based carbon emissions? The case of South Korea. *Environment and Planning B: Urban Analytics and City Science, 52*(3), 545–562.

Murtagh, E., Mair, J., Aguiar, E., Tudor-Locke, C., & Murphy, M. (2020). Outdoor walking speeds of apparently healthy adults: A systematic review and meta-analysis. *Sports Medicine (Auckland, N.Z.), 51*, 125–141. https://doi.org/10.1007/s40279-020-01351-3

Nyka, L., & Burda, I. (2020). Scenario-planning solutions for waterfront flood-prone areas. *Global Journal of Engineering Education, 22*(3), 149–154.

Ogawa, R., Zhang, Y., Theng, V., Guo, Z., Wang, M., & Yoshimura, C. (2023). Capacity assessment of urban green space for mitigating combined sewer overflows in the Tokyo metropolitan area. *Land, 12*(5), 993.

Opach, T., Navarra, C., Rød, J. K., Neset, T. S., Wilk, J., Santos Cruz, S., & Joling, A. (2023). Identifying relevant volunteered geographic information about adverse weather events in Trondheim using the CitizenSensing participatory system. *Urban Anal. City Sci., 50*, 1806–1821.

Patimisco, L., Annunziata, A., & Murgante, B. (2024). *Spatial and configurational analysis for the implementation of the 15-Minute City model. The case study of Perugia, Italy (pp. 681–692)*. Springer Nature. https://doi.org/10.1007/978-3-031-54118-6_60

Petrova-Antonova, D., Murgante, B., Malinov, S., Nikolova, S., & Ilieva, S. (2025). Walkability analysis of Sofia's neighborhoods powered by 15-minute city concept. *Cities, 165*, Article 106171.

Pozoukidou, G., & Angelidou, M. (2022). Urban planning in the 15-minute city: Revisited under sustainable and smart city developments until 2030. *Smart Cities, 5*(4), 1356–1375.

Pozoukidou, G., & Chatziyiannaki, Z. (2021). 15-Minute City: Decomposing the new urban planning Eutopia. *Sustainability*. https://doi.org/10.3390/SU13020928

Quagliolo, C., Roebeling, P., Matos, F., Pezzoli, A., & Comino, E. (2023). Pluvial flood adaptation using nature-based solutions: An integrated biophysical-economic assessment. *Science of the Total Environment, 902*, Article 166202.

Ren, S., He, K., Girshick, R., & Sun, J. (2016). Faster R-CNN: Towards real-time object detection with region proposal networks. *IEEE Transactions on Pattern Analysis and Machine Intelligence, 39*(6), 1137–1149.

de Rijke, H., Saunders, P., & Gulsrud, N. M. (2025). A systematic review of blue-green infrastructure's role and relevance in the mitigation and management of climate-induced hazards in x-minute cities. *Urban Research and Practice*. https://doi.org/10.1080/02697459.2025.2516529

Samól, P. (2018). *Młode Miasto Gdańsk (1380–1455) i jego patrymonium* (pp. 1–422). Uniwersytet Gdański.

Saunders, L. (2017). Healthy cities. *Urban Design Journal, 142*, 12–39.

Sdoukopoulos, A., Papadopoulos, E., Verani, E., & Politis, I. (2024). Putting theory into practice: A novel methodological framework for assessing cities' compliance with the 15-min city concept. *Journal of Transport Geography, 114*, Article 103771.

Sepe, M. (2010). Liveability, quality and place identity in the contemporary city: How to monitor and mitigate the impact of globalization on urban spaces. *Journal of Place Management and Development, 3*(3), 221–246.

Sepe, M. (2023). *Designing healthy and liveable cities*. London-New York: Routledge.

Shartova, N., Mironova, E., Varentsov, M., Grischenko, M., & Konstantinov, P. (2024). Exploring intra-urban thermal stress vulnerability within 15-minute city concept: Example of heat waves 2021 in Moscow. *Sustainable Cities and Society, 114*, Article 105729.

Simon, C. (2022). *Portland's 20-minute neighborhoods after ten years: How a planning initiative impacted accessibility*. University of Washington.

Song, H., Zhai, S., & Luo, J. (2022). Improving the spatial accessibility of community-level healthcare service toward the "15-Minute City" goal in China. *ISPRS International Journal of Geo-Information, 11*, 436. https://doi.org/10.3390/ijgi11080436

Tabatabaei, N. S. (2025). Designing small urban green spaces for equity: A framework for environmental justice. *Journal of Salutogenic Architecture, 4*(1), 15–32.

Tóth, B., Weynants, M., Pásztor, L., & Hengl, T. (2017). 3D soil hydraulic database of Europe at 250 m resolution. *Hydrological Processes, 31*(14), 2662–2666.

Ulloa-Leon, F., Correa-Parra, J., Vergara-Perucich, F., Cancino-Contreras, F., & Aguirre-Nuñez, C. (2023). "15-Minute City" and elderly people: Thinking about healthy cities. *Smart Cities.*. https://doi.org/10.3390/smartcities6020050

USDA NRCS. (1986). *Urban hydrology for small watersheds. Technical release 55 (TR-55)*. Washington, DC: Natural Resources Conservation Service, U.S. Department of Agriculture.

Verma, A., Verma, M., Rahul, T., Khurana, S., & Rai, A. (2019). Measuring accessibility of various facilities by walking in world's largest mass religious gathering – Kumbh Mela. *Sustainable Cities and Society*. https://doi.org/10.1016/J.SCS.2018.11.038

Vich, G., Gómez-Varo, I., & Marquet, O. (2023). Measuring the 15-Minute City in Barcelona. A geospatial three-method comparison. In *Resilient and sustainable cities* (pp. 39–60).

Wen, W., Zhang, W., & Deng, H. (2023). Research on urban road network evaluation based on fractal analysis. *Journal of Advanced Transportation, 2023*(1), Article 9938001.

Wolff, M. (2021). Taking one step further–Advancing the measurement of green and blue area accessibility using spatial network analysis. *Ecological Indicators, 126*, 107665.

Ye, X., She, B., & Benya, S. (2018). Exploring regionalization in the network urban space. *Journal of Geovisualization and Spatial Analysis, 2*, 1–11. https://doi.org/10.1007/s41651-018-0013-y

Zboinska, M. A., Cudzik, J., Juchnevic, R., & Radziszewski, K. (2015). A design framework and a digital toolset supporting the early-stage explorations of responsive kinetic building skin concepts. *Smart and responsive design, 2*, 715–725.

Zhang, H., Wu, C., Zhang, Z., Zhu, Y., Lin, H., Zhang, Z., … Smola, A. (2022). Resnest: Split-attention networks. In *Proceedings of the IEEE/CVF conference on computer vision and pattern recognition* (pp. 2736–2746).

Zhang, K. (2022). An alternative approach to post-industrial rejuvenation in Westport waterfront. *Baltimore. SHS Web of Conferences, 148*, Article 03034. https://doi.org/10.1051/shsconf/202214803034

Zhao, S., Liu, S., Xu, C., Yuan, W., Sun, Y., Yan, W., Zhao, M., Henebry, G., & Fang, J. (2018). Contemporary evolution and scaling of 32 major cities in China. *Ecological applications : a publication of the Ecological Society of America, 28*(6), 1655–1668. https://doi.org/10.1002/eap.1760

Zhou, B., Zhao, H., Puig, X., Fidler, S., Barriuso, A., & Torralba, A. (2017). Scene parsing through ade20k dataset. In *Proceedings of the IEEE conference on computer vision and pattern recognition* (pp. 633–641).

Zhou, L., Li, Y., Cheng, J., Qin, Y., Shen, G., Li, B., … Li, S. (2023). Understanding the aesthetic perceptions and image impressions experienced by tourists walking along tourism trails through continuous cityscapes in Macau. *Journal of Transport Geography, 112*, Article 103703.

Zhu, J. (2023). Public space and its publicness in people-oriented urban regeneration: A case study of Shanghai. *Journal of Urban Affairs*. https://doi.org/10.1080/07352166.2023.2279597